

A Spitzer¹ Infrared Spectrograph² Survey of Warm Molecular Hydrogen in Ultra-luminous Infrared Galaxies

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ABSTRACT

We have conducted a survey of Ultra-luminous Infrared Galaxies (ULIRGs) with the Infrared Spectrograph on the Spitzer Space Telescope, obtaining spectra from 5.0–38.5 μm for 77 sources with $0.02 < z < 0.93$. Observations of the pure rotational H_2 lines S(3) 9.67 μm , S(2) 12.28 μm , and S(1) 17.04 μm are used to derive the temperature and mass of the warm molecular gas. We detect H_2 in 77% of the sample, and all ULIRGs with $F_{60\mu\text{m}} > 2$ Jy. The average warm molecular gas mass is $\sim 2 \times 10^8 M_\odot$. High extinction, inferred from the 9.7 μm silicate absorption depth, is not observed along the line of sight to the molecular gas. The derived H_2 mass does not depend on $F_{25\mu\text{m}}/F_{60\mu\text{m}}$, which has been used to infer either starburst or AGN dominance. Similarly, the molecular mass does not scale with the 25 μm or 60 μm luminosities. In general, the H_2 emission is consistent with an origin in photo-dissociation regions associated with star formation. We detect the S(0) 28.22 μm emission line in a few ULIRGs. Including this line in the model fits tends to lower the temperature by ~ 50 –100 K, resulting in a significant increase in the gas mass. The presence of a cooler component cannot be ruled out in the remainder of our sample, for which we do not detect the S(0) line. The measured S(7) 5.51 μm line fluxes in six ULIRGs implies $\sim 3 \times 10^6 M_\odot$ of hot (~ 1400 K) H_2 . The warm gas mass is typically less than one percent of the cold gas mass derived from ^{12}CO observations.

Subject headings: molecular hydrogen – galaxies: ultraluminous – infrared: galaxies — galaxies: AGN — galaxies: starburst

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1. Introduction

Ultra-luminous infrared galaxies (ULIRGs) are the most luminous objects in the local universe. These objects appear to be mergers of dusty, gas-rich disk galaxies (e.g., Sanders & Mirabel 1996; Moorwood 1996). A direct result of this dusty and large optical depth environment is that they radiate 90% or more of their total energy in the far-infrared, typically with $L_{8-1000\mu m} \geq 10^{12} L_{\odot}$. The bolometric luminosities and space densities of ULIRGs in the local universe (i.e., $z \leq 0.1$) are similar to those of QSOs (Soifer et al. 1987; Sanders & Mirabel 1996). It was proposed by Sanders et al. (1988) that most ULIRGs are powered by dust-enshrouded QSO’s in the late phases of a merger. A classic example of this is Mrk 231, where the detection of broad ($\sim 10,000 \text{ km s}^{-1}$) hydrogen emission lines (Arakelian et al. 1971; Adams & Weedman 1972) and radio jets (Lonsdale et al. 2003) provides direct evidence for the central active galactic nucleus (AGN). The final state of a ULIRG may be a large elliptical galaxy with a central massive quiescent black hole (Kormendy & Sanders 1992). The ratio of the $25 \mu m$ to $60 \mu m$ flux densities, as measured with the Infrared Astronomical Satellite (IRAS, Neugebauer et al. 1984), has been used to classify ULIRGs. This ratio reflects the globally averaged dust temperature of the galaxy, which is typically 50 - 100 K. The ULIRGs are classified as either “warm” ($F_{25\mu m}/F_{60\mu m} \geq 0.2$) and possibly AGN dominated, or “cold” ($F_{25\mu m}/F_{60\mu m} < 0.2$), with a possible dominant contribution to the overall luminosity from massive star formation. Although luminous mergers are rare in the local universe, it has been proposed that ULIRGs may make a significant contribution to the star formation density at $z \geq 1$ (e.g., Elbaz & Cesarsky 2003).

Molecular hydrogen is the primary component of the dense gas in galaxies and the most abundant molecule in the Universe. Stars are not only formed from molecular clouds, but the H_2 acts as a coolant enabling the star formation to proceed. H_2 may also act as a coolant facilitating the accretion of material onto a central AGN. Prior to space borne missions large quantities of molecular hydrogen in the central regions of ULIRGs has been inferred from detections of rotational transitions of ^{12}CO (e.g., Sanders, Scoville & Soifer 1991; and references for this sample in Table 4.). A much smaller, hot ($\sim 2000 \text{ K}$) gas component can be observed directly in the near-infrared through ro-vibrational H_2 lines (e.g., Van der Werf et al. 1993).

In this paper, we have used observations with the Spitzer Space Telescope (Werner et al. 2004) to directly probe the warm ($\gtrsim 100 \text{ K}$) molecular hydrogen component through pure rotational transitions, where the upper levels are populated via UV pumping, formation of H_2 in excited states, or collisional excitation. Four heating mechanisms have been proposed for the gas: (1) grain photoelectric heating in photo-dissociation regions (PDRs), (2) shock heating from outflows, SNRs and large scale streaming motions in spiral arms and bars,

(3) X-ray heating of gas from AGN, SNRs and cooling flows, and (4) cosmic-ray heating. H_2 has two independent states: ortho- H_2 , where the nuclear spins are parallel, and para- H_2 , where the spins are anti-parallel. The rotational states have even spatial symmetry in the para- H_2 and odd spatial symmetry in the ortho- H_2 . An ortho-to-para ratio of 3 is found for gas of typical temperature $T \sim 300$ K. The proton exchange mechanism is a pathway to set up and maintain these LTE ratios. H_2 is highly symmetric and has no permanent dipole moment. All the rotational transitions within the electronic ground state are quadrupolar, with correspondingly low spontaneous Einstein A coefficients. This makes the emission lines very weak, and until the advent of Spitzer, difficult to observe in all but the brightest galaxies. Valentijn et al. (1996) published the first detection of the H_2 S(0) $28.22 \mu\text{m}$ transition in the galaxy NGC 6946, using the Short Wavelength Spectrometer (SWS) on the Infrared Space Observatory (ISO). Subsequently, Rigopoulou et al. (2002) published a survey of H_2 in 12 starburst and 9 Seyfert galaxies using ISO. H_2 has been detected in only two ULIRGs, Arp 220 (Sturm et al. 1996) and NGC 6240 (Lutz et al. 2003). A review of the ISO H_2 observations is given in Habart et al. (2005).

In order to investigate the properties for a statistically representative sample of the local ULIRG population, we have selected 110 ULIRGs having with redshifts between 0.02 and 0.93 for observation with Spitzer’s Infrared Spectrograph (IRS, Houck et al. 2004), as part of the IRS GTO program. These sources are chosen from the complete Bright Galaxy Sample (Soifer et al. 1987), the 1 Jy (Kim & Sanders 1998) and 2 Jy (Strauss et al. 1992) samples, and the FIRST/IRAS radio-far-infrared sample of Stanford et al. (2000). Armus et al. (2004) published the first results from this survey for Mrk 1014, Mrk 463, and UGC 5101. Two other papers discussing NGC 6240 and the ten ULIRGs in the IRAS bright galaxy sample (Soifer et al. 1987) are in press (Armus et al. 2006a & 2006b, respectively). In this paper we use the unprecedented sensitivity of the IRS to assess the warm H_2 component in a sub-sample of 77 ULIRGs. All sources were detected at $60 \mu\text{m}$ with IRAS. Forty-eight of the ULIRGs in our sample are classified as “cold” (i.e., $F_{25\mu\text{m}}/F_{60\mu\text{m}} < 0.2$) and likely starburst dominated. The remaining twenty-nine ULIRGs are “warm” (i.e., $F_{25\mu\text{m}}/F_{60\mu\text{m}} \geq 0.2$), and are probably powered by an obscured active nucleus. The basic properties of the sample are listed in Table 1.

The Spitzer IRS wavelength coverage encompasses the pure rotational S(0) $28.22 \mu\text{m}$ through S(7) $5.51 \mu\text{m}$ transitions. The relative line strengths allow the determination of the temperature and mass of the warm H_2 gas. In §2 we detail the observations and data reduction, and in §3 we present the results. In general the analysis of the warm molecular gas is approximated with a single temperature model. However, we detected the S(0) line in three ULIRGs, which can lower the derived warm gas temperature. Additionally, in some systems we detect the S(7) line, and we use this to model a hot gas component. In the discussion

section (§4) we investigate the warm gas mass as a function of the average global dust temperature. We also assess the warm gas fraction with respect to the cold gas mass estimates available in the literature. Our conclusions are presented in §5. Throughout the paper we adopt a flat Λ -dominated Universe ($H_o = 71 \text{ km s}^{-1}\text{Mpc}^{-1}$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, and $\Omega_k = 0$).

2. Observations And Data Reduction

The data presented here were obtained using the IRS. In low resolution mode (IRS-LORES) there are two spectrometers with a resolving power $64 \leq \frac{\lambda}{\Delta\lambda} \leq 128$. Short-low (IRS-SL) operates between $5.2 \mu\text{m}$ and $7.7 \mu\text{m}$ in short-low 2 (IRS-SL2) and $7.4 - 14.5 \mu\text{m}$ in short-low 1 (IRS-SL1). Long-low (IRS-LL) gives coverage from $14.0 - 21.3 \mu\text{m}$ in long-low 2 (IRS-LL2) and $19.5 - 38.0 \mu\text{m}$ in long-low 1 (IRS-LL1). The two high resolution spectrometers (IRS-HIRES) have a resolving power, $\frac{\lambda}{\Delta\lambda} \sim 600$. Short-high (IRS-SH) encompasses the range $9.9 - 19.6 \mu\text{m}$ and Long-high (IRS-LH) spans $18.7 - 37.2 \mu\text{m}$. The observations were made in the IRS Staring Mode Astronomical Observing Template (AOT). A high-accuracy blue peak-up, using either a star from the 2MASS catalog (Cutri et al. 2003) or the source itself, was executed in order to accurately place our targets on the IRS slits. The observation log is given in Table 2. The IRS is fully described in Houck et al. (2004) and the observing mode details are presented in chapter 7 of the Spitzer Observers Manual (SOM)¹.

The spectral data were processed as far as the un-flatfielded two dimensional image using the standard IRS S11 pipeline (see the SOM). The spectra were then extracted and sky subtracted using the SMART analysis package (Higdon et al. 2004). To maximize the signal-to-noise in the final spectra the data were extracted using a column whose width in the cross-dispersion direction scales with the instrument point spread function. The spectra were flat-fielded and flux-calibrated by extracting and sky subtracting un-flatfielded observations of the calibration stars, HR 6348 (IRS-SL), HD 173511 (IRS-LL), and HD 163588 (IRS-HIRES), and dividing these data by their respective templates (Cohen et al. 2003) to generate a one-dimensional relative spectral response function (RSRF). The RSRF was then applied to the TARGET observations to produce the final spectra. The residual sky was subtracted from the IRS-LORES data using the off-source observations, which are part of the staring mode AOT. For the IRS-HIRES data, a spectrum of the zodiacal light on the date of the observation was generated using the Spitzer Planning and Observation Tool (SPOT. This uses the zodiacal light model of Reach et al. 2003), scaled using the IRS-

¹<http://ssc.spitzer.caltech.edu/documents/som>

HIRES apertures, and subtracted from the spectra. The IRS-HIRES spectra were de-fringed in SMART. The spectra were scaled to match the $25\ \mu\text{m}$ flux densities measured by IRAS. Sources lacking a measured IRAS $25\ \mu\text{m}$ flux density were observed with the IRS’ peak-up arrays, allowing us to scale the spectra to match the source’s $22\ \mu\text{m}$ flux density. The scaling factors, which are multiplicative, are listed in Table 2. The ULIRG IRAS 09022-36 required an extremely large scaling factor (~ 17) to bring the SH and $25\ \mu\text{m}$ flux density measured by IRAS into agreement. We chose not to scale the data. We are confident in the detection of the S(1) line. However, the absolute flux calibration of this source is uncertain.

Most of the mid-infrared emission in ULIRGs arises in a region of order one to a few kiloparsecs in size, which are spatially unresolved with respect to the IRS slits.² To check this assumption we examined the IRS-SL2 data. This has the highest spatial resolution with $1.8''$ per pixel. The IRS-SL2 data was collapsed in the dispersion direction and a Gaussian was fit to the profile. Our calibration star, HR 6348 is fit with a Gaussian, with a FWHM of $2.88''$. Only IRAS 09022-3615, IRAS 12112+0305 and IRAS 14348-1447 show evidence of significant source extension i.e. $\text{FWHM} \geq 1.5 \times \text{FWHM}_{\text{star}}$. Their FWHM are 3.0, 1.7 and 1.7 times that of the calibration star, respectively. Both IRAS 12112+0305 and IRAS 14348-1447 are known doubles with nuclei separated by 2.9 and $3.4''$, respectively and the $5''$ Gaussian FWHM corresponds to a linear diameter of 8 and 9 kpc, respectively. Our observations were centered on the NE nucleus in IRAS 12112+0305 and the SW nucleus in IRAS 14348-1447, as these are the dominant nuclei in the near-infrared and in CO (Evans et al. 2002 and Evans, Surace & Mazzarella 2000). For IRAS 09022-3615 there was a pointing problem and the PSF is poorly sampled. No additional correction to line fluxes has been made to account for the extended emission.

Blending is a problem for the higher rotational lines, which can only be observed with the IRS-LORES. The S(6) $6.1\ \mu\text{m}$ line, for example, can be blended with PAH emission at $6.2\ \mu\text{m}$, S(5) $6.9\ \mu\text{m}$ line can be blended with the [Ar II] $7.0\ \mu\text{m}$ line and PAH emission at $7.0\ \mu\text{m}$, and the S(4) $8.0\ \mu\text{m}$ line can be blended with PAH emission at $7.8\ \mu\text{m}$ and $8.3\ \mu\text{m}$. NGC 6240 is the only source in our sample where the emission is bright enough to be detected in these transitions (Armus et al. 2006a).

The resulting S(3), S(2), and S(1) H_2 line profiles, averaged over the two slit-nod positions, are shown in the first, second, and third columns of Figure 1, respectively. The S(0) detections, which indicates a somewhat cooler H_2 component, are shown in Figure 2, while the S(7) detections, which arise from a hotter H_2 component, are shown in Figure 3. In Table

²The slit sizes for the IRS modules are SL2: $3''.6 \times 57''$, SL1: $3''.7 \times 57''$, LL2: $10''.5 \times 168''$, LL1: $10''.7 \times 168''$, SH: $4''.7 \times 11''.3$, LH: $11''.1 \times 22''.3$

3 we list the line fluxes and upper-limits. We find the dominant source of uncertainty in the line fluxes to be the difference between the fit to the line profiles in the two slit-nod positions. Upper limits are calculated using the residuals (rms) from a 0-order fit to the continuum. We take the 3σ upper limit to be $3 \times \text{rms} \times \text{FWHM}$. No extinction correction has been applied to the observed line fluxes. Determining the correct extinction factor is inherently difficult, and we address this in §3.2, where we discuss the location of the warm molecular hydrogen gas. We calculate a lower limit to the fraction of the total far-infrared luminosity, L_{IR}^3 , radiated in the H_2 for those sources that have at least one measured emission line flux. The lower limit is the sum of the line luminosities that were fit with a Gaussian, divided by L_{IR} . Typically $\sim 0.01\%$ of the total far-infrared luminosity is radiated in the H_2 rotational lines.

3. Results

Before deriving the physical properties of the warm molecular hydrogen we will take a quick look at the sample to check for systematic offsets and biases. All seventy-seven ULIRGs were observed using IRS-LORES. However, the brighter sources were also observed in IRS-HIRES, fifteen with IRS-LH and thirty-seven with both IRS-SH and IRS-LH. We find no significant difference in the H_2 detection rate for these IRS-LORES and IRS-HIRES observations. For IRS-HIRES the detection rate is 35/50 ($70 \pm 12\%$) as compared to 51/77 ($66 \pm 9\%$) for IRS-LORES observations. Twenty-five sources have both IRS-LORES and IRS-HIRES measurement of the S(1) line. On average the IRS-HIRES measurement is $90 \pm 31\%$ of the IRS-LORES value. Twenty-three sources have both IRS-LORES and IRS-HIRES measurements of the S(3) line. Two sources, IRAS 08311-2459 and IRAS 19254-7245, have large line flux uncertainties. The remaining twenty-one sources have an average IRS-HIRES measurement that is $100 \pm 33\%$ of the average IRS-LORES line flux. There is no evidence for a significant systematic difference between high- and low-resolution line flux measurements.

The sample contains a mixture warm and cold sources. Eighteen of the twenty-nine warm ULIRGs were detected in H_2 ($62 \pm 15\%$), whereas forty-one of the forty-eight cold ULIRGs were detected ($85 \pm 13\%$). There is thus no significant statistical difference in the detection rate for the two sub-populations.

The likelihood for detecting H_2 is flux limited. There are forty sources in our sample

³ $L_{\text{IR}} = L_{8-1000\ \mu\text{m}}$ is defined to be $4\pi d_L^2 F_{\text{IR}}$ in units of L_\odot , where d_L is the luminosity distance, and $F_{\text{IR}} = 1.8 \times 10^{-14} (13.48 F_{12\mu\text{m}} + 5.16 F_{25\mu\text{m}} + 2.58 F_{60\mu\text{m}} + F_{100\mu\text{m}})$ in W m^{-2} (Sanders and Mirabel 1996).

that have an IRAS 60 μm flux density ≤ 2 Jy. This includes the eighteen sources in the sample for which we do not detect any molecular hydrogen emission and twelve of the sixteen sources for which we only detect a single emission line. This suggests a detection limit based on our choice of integration time. We detect molecular hydrogen in all sources with 60 μm flux densities > 2 Jy, irrespective of the warm/cold classification.

3.1. Warm H₂ Gas

To derive the mass of warm molecular hydrogen we assume that all of our sources are spatially unresolved by the IRS and that the emission is optically thin. The critical densities of the $J = 2, 3$, and 4 levels are relatively low ($n_{\text{cr}} < 10^3 \text{ cm}^{-3}$) and we assume that the populations are in LTE. Adopting an ortho-to-para ratio of 3, we constructed an excitation diagram for each source.⁴ This is simply the natural logarithm of the number of molecules divided by the statistical weight in the upper level of each transition versus the energy level. If the H₂ is characterized by a single temperature, the data will lie on a straight line, with the excitation temperature (T_{ex}) being the reciprocal of the slope. The excitation diagram for IRAS 00188-0856 is shown in Figure 4. This is a typical example of single component fit, which is the case for the majority of our sources. The mass of warm H₂ can be derived from the line luminosity and the excitation temperature. For example, using luminosity of the S(1) 17.04 μm (ortho) line, the energy of a given level is given by $E_J = 85kJ(J+1)$, where k is the Boltzmann constant. The total mass (M_{Total}), is $\frac{4}{3}M_o$, where M_o is the mass of gas in the ortho state and $M_o = m_{\text{H}_2}N_T$, with m_{H_2} being the molecular mass of H₂ and N_T is the total number of molecules. However, $N_T = \frac{N_J}{f_J}$, where N_J is the number of molecules in the J^{th} state, $N_J = \frac{L(J)}{A_J\Delta E_J}$. Here, $L(J)$ is the line luminosity, A_J is the Einstein A coefficient, $\Delta E_J = h\nu_J$, where h is Planck's constant and ν_J is the frequency of the emission line. f_J is the partition function for the J^{th} state, $f_J = \frac{g_J e^{-\frac{E_J}{kT_{\text{ex}}}}}{\sum_{J', \text{ortho}} g_{J'} e^{-\frac{E_{J'}}{kT_{\text{ex}}}}}$, where g_J is the statistical weight for a given state.

We derived an excitation temperature for approximately half of our ULIRG sample (43 sources), that had detections in at least two transitions. The mean T_{ex} for this sub-sample is 336 ± 15 K. Table 3 also lists an additional sixteen sources in which we only see a single ortho-molecular hydrogen line. We used the mean T_{ex} to estimate the warm gas mass in these sources. The warm gas masses range from 10^7 to $10^9 M_{\odot}$, with an average value of \sim

⁴The complete set of excitation diagrams is available at <http://isc.astro.cornell.edu/~sjuh/ulirgs/h2/excitation-diagrams.html>.

$2 \times 10^8 M_{\odot}$. The warm molecular hydrogen excitation temperatures and masses are given in Table 4.

3.2. Extinction and the Ortho-to-Para Ratio

It is inherently difficult to derive the correct extinction along a given line of sight. Using optical depths derived in the mid-infrared alleviates the problem of extrapolating from a measurement made in the optical. However, the geometry of the emitting sources and whether the derived optical depth should be approximated as a foreground screen or material mixed with the warm gas, either in clumpy or uniform medium, are all highly uncertain. Figure 5 shows the combined low-res and high-res spectrum of Mrk 273 from $6.5 \mu\text{m}$ to $13.5 \mu\text{m}$. The deep silicate absorption feature corresponds to an optical depth of $\tau_{9.7\mu\text{m}} \sim 2$, implying an $A_V \sim 20 - 40$ (Roche & Aitken 1985). For molecular hydrogen at a temperature of 380 K in LTE with an ortho-to-para ratio of 3, the intrinsic S(2)/S(3) line ratio is 0.56. If the H_2 has the same extinction implied by the depth of the silicate absorption trough, the line ratio will be in the range 1.05 - 1.95 when the absorbing material in a foreground screen, and 0.74 - 0.90 for a mixture of dust and gas. The observed S(2)/S(3) line ratio is 0.54 ± 0.08 , which is consistent with the unextincted value. In Figure 6 we plot T_{ex} versus the observed H_2 S(1)/S(3) line ratio, which is independent of the ortho-to-para ratio. The data represent the twenty-seven galaxies where at least three $J \leq 4$ lines are detected in the IRS-HIRES observations. NGC 6240 and IRAS 12112+0305 are not included in this selection, as their excitation diagrams are best described by multi-component gas, as we describe more fully in the next section. The figure shows that the majority of the sources have line ratios which are consistent with the theoretical value for no extinction. From this we infer that the absorbing material along the line of sight to the central AGN does not lie in a screen between us and the warm molecular gas. If the H_2 emission originates from a massive and dusty circum-nuclear torus, then the gas and dust are mixed, and the bulk of the emission must arise from regions with optical depths less than three, as described by Burton, Hollenback and Tielens (1992). Alternately, the H_2 emission may also arise in PDRs associated with massive star formation. Higher angular resolution observations are needed to measure the relative fractions emitted from a dusty torus and from PDRs.

Using the same twenty-seven sources we can test our assumption that the ortho-to-para ratio is three. In Figure 7, the dashed line shows the theoretical H_2 S(1)/S(2) line ratio as a function of T_{ex} , and we have over-plotted the observed line ratios. The data are consistent with both the assumed ortho-para-ratio of three with essentially no extinction. In both Figures 6 and 7, the ULIRG IRAS 15462-0450 shows the largest departure from the

theoretical curves, which we attribute to calibration difficulties.

3.3. Multi-Temperature H₂ Gas

ULIRGs are complex systems and we would not expect the H₂ gas to be at a single temperature. NGC 6240 (Armus et al. 2006a) is the only system in our sample where we detect all the S(0) through S(7) rotational lines. Its excitation diagram is shown in Figure 8. The S(3) through S(7) lines are well fit by a hot H₂ component, with $T_{\text{ex}} = 1327 \pm 36$ K. The S(7) line flux implies a hot molecular hydrogen mass of $(4.1 \pm 0.8) \times 10^6 M_{\odot}$. Subtracting this component’s contribution from the S(0) through S(3) lines gives a second, cooler, H₂ component, with $T_{\text{ex}} = 292 \pm 6$ K. The measured S(0) line flux weights the fit to lower temperatures and correspondingly larger H₂ masses. The warm gas mass inferred for the S(0) line flux is $(6 \pm 3) \times 10^8 M_{\odot}$.

Besides NGC 6240, we detect the S(0) line in only two other sources, IRAS 12112+0305 and IRAS 13342+3932. Likewise, the S(7) line is detected in only six sources, NGC 6240, Arp 220, IRAS 06301-7954, IRAS 12032+1707, IRAS 12112+0305, and IRAS 17068+4027 with S/N > 3. Figure 9 shows the excitation diagrams for these six sources. When the S(7) line is detected, a fit is first made to the S(7) and S(3) lines to determine the temperature of the hot H₂ component. In Arp 220, for example, the derived excitation temperature is 1435 ± 120 K. This component’s contribution is then subtracted from the S(3) through S(0) lines, so the T_{ex} and mass of the cooler H₂ component can be estimated. The derived T_{ex} and H₂ masses are listed in Table 4. In IRAS 13342+3932 the fit is heavily weighted towards a low temperature, as only the S(0) and S(1) lines are detected. The resulting gas mass is an order of magnitude larger than the masses calculated for NGC 6240 and IRAS 12112+0305. A similar decrease of ~ 50 -100 K in the temperature and increase in the mass by a factor of ten is obtained for both NGC 6240 and IRAS 12112+0305, if only the S(0) and S(1) lines are used in the second temperature fit. This suggests that our result for both the mass and temperature in IRAS 13342+3932 is strongly biased by our non-detection of the S(2) and S(3) lines. Using the average temperature for the sample ($T_{\text{ex}} = 336 \pm 15$ K), we infer a mass of $\sim 2 \times 10^8 M_{\odot}$, which is probably a better estimate of the warm H₂ gas mass, and more in keeping with the rest of the sample. The average hot gas temperature is 1400 ± 60 K, with an associated molecular mass of $(3 \pm 2) \times 10^6 M_{\odot}$. The warm, $T_{\text{ex}} \sim 340$ K H₂ component, with $M_{\text{H}_2} \sim 10^8 - 10^9 M_{\odot}$, thus represents the bulk of the measured gas mass.

4. Discussion

4.1. Warm and Cold ULIRGs

Figure 10 shows the derived H_2 mass as a function of the IRAS 25 μm and 60 μm flux density ratio ($F_{25\mu\text{m}}/F_{60\mu\text{m}}$). The vertical dashed line corresponds to $F_{25\mu\text{m}}/F_{60\mu\text{m}} = 0.2$, which is used to separate “cold” and “warm” ULIRGs. There are no obvious trends. That is, there appears to be no systematic tendency for starburst or AGN powered ULIRGs to have systematically larger (or smaller) masses of warm H_2 .

Likewise, there is no clear dependence on far-infrared luminosity. Figure 11 shows the derived warm H_2 mass as a function of the 60 μm specific luminosity ($L_{60\mu\text{m}}$), which we define as $4\pi d_L^2 F_{60\mu\text{m}}$ in units of W Hz^{-1} . Here, d_L is the source’s luminosity distance. The twenty-seven ULIRGs in the plot all have $z < 0.1$, which ensures that the IRAS 60 μm flux densities correspond to nearly identical rest-frame wavelengths. A possible tendency for warm H_2 mass to increase with far-infrared luminosities in excess of $L_{60\mu\text{m}} = 3 \times 10^{25} \text{ W Hz}^{-1}$ is significantly weakened by a number of outliers with higher H_2 masses.

The observed S(1) line intensity is typically $\sim 10^{-4} \text{ erg cm}^{-2} \text{ s}^{-1}$, which is consistent with the Burton, Hollenbach, and Tielens (1992) PDR models with density $\sim 10^4\text{--}10^5 \text{ cm}^{-3}$ and far-UV fields of $\sim 10^3\text{--}10^4 G_0$. Here, G_0 is the local interstellar far-UV radiation field, determined to be $1.6 \times 10^{-3} \text{ ergs s}^{-1} \text{ cm}^{-2}$ (Habing 1968). This is consistent with PDRs being a large contributor to the warm H_2 emission. Of course there can also be a significant shock component in some ULIRGs. Constraining the contribution of shock excitation will require observations of ro-vibrational transitions in the near-infrared.

4.2. Fractional Warm Gas Mass

In Table 4 we have listed the cold molecular hydrogen mass derived from $^{12}\text{CO}(1\text{--}0)$ observations of thirty ULIRGs from the literature. These masses range from 10^8 to $10^{11} M_\odot$, with an average cold $M_{\text{H}_2} \sim 4 \times 10^{10} M_\odot$. This is calculated using the standard Milky Way $M_{\text{H}_2}/L_{\text{CO}}$ ratio of $4.6 M_\odot/\text{K km s}^{-1} \text{ pc}^2$ determined from observations of Galactic molecular clouds (Solomon et al. 1987). However, as stressed by Maloney & Black (1988), because the $\text{CO}(1\text{--}0)$ line intensity scales as a modest power of the gas temperature⁵, the molecular hydrogen masses may be *overestimated* by factors of 3–5 in regions of intense star formation or AGN dominance. The density and filling factor of the $^{12}\text{CO}(1\text{--}0)$ emitting regions also affect

⁵ $I_{\text{CO}} \propto T_{\text{kin}}^{1.3}$ for $T_{\text{kin}} \lesssim 30 \text{ K}$, and $I_{\text{CO}} \propto T_{\text{kin}}$ for $T_{\text{kin}} > 30 \text{ K}$.

the measured CO intensity in ways that are difficult to take into account a priori. Solomon et al. (1997) argue that the standard conversion factor is inappropriate for ULIRGs, as the derived masses often exceed the dynamical masses. They argue that in the extreme environments found in the central regions of ULIRGs, the CO emission originates not from self-gravitating clouds, but from an inter-cloud medium, which is bound by the potential of the galaxy or molecular gas pressure, resulting in a smaller M_{H_2}/L_{CO} of $\sim 1.4 M_{\odot}/K \text{ km s}^{-1} \text{ pc}^2$. All of this suggests that the cold molecular masses in Table 4 should be viewed with considerable caution, and likely represent overestimates of the true M_{H_2} . Indeed, use of the α advocated by Solomon et al. (1997) for their ULIRG sample, would both lower the cold H_2 mass and increase the warm H_2 gas fraction by a factor of ~ 3 . However the warm H_2 gas remains a small fraction of the total H_2 mass.

We have H_2 detections for twenty-eight of these sources. Some of the sources do have a warm gas fraction that scales with warm gas mass, but the scatter in the data is large and there is no strong trend. The median fractional warm gas mass is 0.3% of the cold gas mass. Figure 12 shows the warm gas fraction as a function of $F_{25\mu m}/F_{60\mu m}$. Rigopoulou et al. (2002) derived an average gas temperature of ~ 150 K for their sample of local starbursts and AGN, and found the warm gas fraction to as large as 10% in starbursts and up to 35% (with a large scatter) in Seyferts. In nearly half of their sample they did not detect the S(0) line, and the derived temperature is ~ 300 K. The difference between the average warm gas fractions in our ULIRG sample and the local starburst/AGN sample is heavily weighted by the adopted gas temperature, and whether or not the S(0) line is detected. It is likely that the warm gas fraction is similar in both. More sensitive observations of the S(0) line in ULIRGs are needed to fully constrain the ~ 150 K component.

Figure 12 also shows that only 8/28 of ULIRGs with both cold and warm H_2 masses have $F_{25\mu m}/F_{60\mu m} \geq 0.2$, and only one has $F_{25\mu m}/F_{60\mu m} \geq 0.4$. As a result, we are unable to say conclusively if there is a tendency for the warm H_2 mass to depend on dust temperature, i.e., on AGN dominance. While the position of Mrk 463 in the upper-right of the figure is suggestive of such a trend, it may simply be an outlier, like the “cold” IRAS 12112+0305 near the top-left. No increase in the warm gas fraction is measured as a function of either increasing IRAS 25 μm or 60 μm specific luminosity.

5. Conclusions

We have used Spitzer’s IRS to obtain spectra from 5.0–38.5 μm for a large sample of ULIRGs. This sample is bright ($0.1 < F_{60\mu m} \leq 104$ Jy) and have redshifts between 0.02 and 0.93. We have detected line emission from pure rotational transitions of molecular hydrogen

in 77% of the sample, and in all ULIRGs with $F_{60\mu\text{m}} > 2$ Jy. The majority of these sources are modeled with a single temperature H_2 component, with an average excitation temperature (T_{ex}) of 336 ± 15 K. The ULIRGs contain large quantities of warm molecular hydrogen. We find an average mass $2 \times 10^8 M_{\odot}$. Large optical depths, as inferred from the depth of the silicate absorption trough at $9.7 \mu\text{m}$, are not observed along the line of sight to the warm H_2 gas. If the gas originates in a central dusty torus, the medium must be clumpy. The warm H_2 mass does not appear to depend on the IRAS $25 \mu\text{m}$ to $60 \mu\text{m}$ flux density ratio, which is used to classify ULIRGs into “warm” (AGN dominated) and “cold” (starburst dominated) categories. Similarly, the warm H_2 mass does not scale with the specific luminosity at $25 \mu\text{m}$ or $60 \mu\text{m}$. A possible common origin for the gas is from photo-dissociation regions associated with massive star formation.

The single temperature gas model, fitted to the S(1) through S(3) lines, is a simplification and the gas is likely to have multiple temperature components. Detection of the S(0) line will typically lower the derived temperature in the single component fit by 50-100 K, leading to a larger estimated gas mass. This higher gas mass cannot be ruled out in the bulk of our sample for which we do not detect the S(0) line. A hot H_2 gas component is inferred when the S(7) line is detected. This line is detected in six ULIRGs, and is modeled as a $T_{\text{ex}} = 1400 \pm 60$ K H_2 component, with a relatively small mass ($M_{\text{H}_2} \sim 3 \times 10^6 M_{\odot}$).

Using cold molecular gas estimates from ^{12}CO observations in the literature, we find that the warm H_2 mass is typically less than one percent of the cold H_2 mass. The average warm gas fraction could be a few tens of percent, but this requires verification through the detection of the S(0) $28.22 \mu\text{m}$ line, which is difficult using the IRS as the line is situated in a low-sensitivity region of the detector array, and detection of the ^{12}CO line. In general, ULIRGs have a warm mass fraction that is comparable to that found in local starburst and Seyfert galaxies (Rigopoulou et al. 2002).

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Table 1. ULIRG Sample

Object	z	D_L^a (Mpc)	L_{IR}^b ($10^{12}L_\odot$)	$\frac{F_{25\mu m}}{F_{60\mu m}}$
3C273	0.1584	749.3	5.74	0.52
Arp 220	0.0181	77.6	1.45	0.08
IRAS 00188-0856	0.1286	596.3	2.56	0.14
IRAS 00275-0044	0.2420	1203.8	2.62	0.37
IRAs 00275-2859	0.2792	1418.1	3.16	0.25
IRAS 00397-1312	0.2617	1316.5	6.46	0.22
IRAS 00406-3127	0.3424	1797.9	6.25	0.12
IRAS 00476-0054	0.7270	4462.9	8.32	0.11
IRAS 01003-2238	0.1177	541.9	1.95	0.29
IRAS 01199-2307	0.1560	736.6	2.32	0.10
IRAS 02115+0226	0.4000	2160.1	9.65	0.49
IRAS 02433+0110	0.7980	5009.1	8.91	0.23
IRAS 03521+0028	0.1522	716.7	3.65	0.09
IRAS 04114-5117	0.1246	576.2	1.85	0.04
IRAS 04313-1649	0.2680	1352.9	4.48	0.07
IRAS 05189-2524	0.0426	185.7	1.43	0.25
IRAS 06035-7102	0.0795	356.3	1.66	0.11
IRAS 06206-6315	0.0924	418.2	1.69	0.07
IRAS 06301-7934	0.1564	738.7	2.45	0.05
IRAS 06361-6217	0.1596	755.3	1.49	0.10
IRAS 07598+6508	0.1488	699.5	3.37	0.31
IRAS 08311-2459	0.1004	457.0	3.31	0.22
IRAS 08572+3915	0.0584	257.6	1.37	0.23
IRAS 09022-3615	0.0596	263.6	1.91	0.10
IRAS 09463+8141	0.1547	729.8	2.03	0.05
IRAS 10091+4704	0.2460	1226.5	4.55	0.07
IRAS 10398+3247	0.6330	3762.8	6.03	0.04
IRAS 10565+2448	0.0431	188.2	1.09	0.09
IRAS 11119+3257	0.1890	911.1	4.51	0.22
IRAS 12018+1941	0.1686	802.7	3.18	0.21
IRAS 12032+1707	0.2170	1063.8	3.92	0.17
IRAS 12071-0444	0.1284	595.2	2.30	0.22
IRAS 12112+0305	0.0727	324.2	2.12	0.06
IRAS 12514+1027	0.3000	1541.0	5.53	0.27
IRAS 13120-5453	0.0308	133.0	1.73	0.07
IRAS 13218+0552	0.2051	998.4	5.14	0.34
IRAS 13342+3932	0.1793	859.2	1.96	0.02
IRAS 13352+6402	0.2366	1173.3	3.64	0.08
IRAS 13451+1232	0.1220	563.3	1.97	0.35
IRAS 14348-1447	0.0825	370.6	2.24	0.07
IRAS 14378-3651	0.0676	300.7	1.35	0.08
IRAS 14537+1950	0.6400	3814.0	10.49	0.57
IRAS 14548+3349	0.4430	2440.0	2.82	0.18
IRAS 15001+1433	0.1627	771.7	2.79	0.09
IRAS 15206+3342	0.1244	575.3	1.73	0.20

Table 1—Continued

Object	z	D_L^a (Mpc)	L_{IR}^b ($10^{12}L_\odot$)	$\frac{F_{25\mu m}}{F_{60\mu m}}$
IRAS 15250+3609	0.0554	244.0	1.13	0.18
IRAS 15462-0450	0.0998	453.8	1.59	0.15
IRAS 16124+3241	0.7100	4334.3	4.57	0.31
IRAS 16334+4630	0.1910	921.9	2.89	0.08
IRAS 17068+4027	0.1791	858.2	2.43	0.09
IRAS 17179+5444	0.1475	692.5	1.98	0.15
IRAS 17208-0014	0.0430	187.8	2.50	0.05
IRAS 17233+3712	0.6890	4176.6	10.51	0.25
IRAS 17463+5806	0.3090	1594.8	2.69	0.06
IRAS 18030+0705	0.1458	683.8	1.90	0.30
IRAS 18443+7433	0.1347	627.4	2.08	0.09
IRAS 19254-7245	0.0617	273.1	1.21	0.23
IRAS 19297-0406	0.0857	386.1	2.56	0.08
IRAS 19458+0944	0.0999	454.6	2.32	0.07
IRAS 20037-1547	0.1919	926.7	3.66	0.17
IRAS 20087-0308	0.1057	482.5	2.80	0.05
IRAS 20100-4156	0.1296	601.3	4.48	0.07
IRAS 20414-1651	0.0871	392.5	1.70	0.08
IRAS 20551-4250	0.0427	186.2	1.10	0.15
IRAS 21272+2514	0.1508	709.6	1.40	0.36
IRAS 22491-1808	0.0773	346.0	1.54	0.10
IRAS 23128-5919	0.0446	194.9	1.07	0.15
IRAS 23129+2548	0.1791	858.2	3.13	0.07
IRAS 23365+3604	0.0645	286.0	1.47	0.11
IRAS 23498+2423	0.2120	1036.3	2.99	0.20
IRAS 23529-2119	0.4303	2356.5	4.68	0.48
Mrk 231	0.0422	184.2	3.70	0.25
Mrk 273	0.0378	164.3	1.42	0.10
Mrk 463E	0.0504	221.0	0.60	0.72
Mrk 1014	0.1631	773.6	4.12	0.24
NGC 6240	0.0245	105.4	0.69	0.15
UGC 5101	0.0400	174.3	1.00	0.09

^aThe luminosity distance in Mpc.

^bThe 8-1000 μm far-infrared luminosity, defined as $L_{IR} = 4\pi d_L^2 F_{IR}$ in units of L_\odot , with $F_{IR} = 1.8 \times 10^{-14}$ ($13.48 F_{12\mu m} + 5.16 F_{25\mu m} + 2.58 F_{60\mu m} + F_{100\mu m}$), in units of $W m^{-2}$ (Sanders and Mirabel 1996).

Table 2. Observational Parameters

Object	RA	Dec	Date Obs.	Exec. Time (min)	Scale Factor to IRAS 25 μ m flux density					
	(J2000)	(J2000)			SL2	SL1	LL2	LL1	SH	LH
3C273	12:29: 6.67	2: 3: 8.10	2005-06-07	21.7	1.01	1.03	0.97	0.98	0.96	0.78
Arp220	15:34:57.24	23:30:11.70	2004-02-29	42.8	1.00	1.14	0.97	0.92	1.08	1.02
IRAS00188-08	0:21:26.48	-8:39:27.10	2003-12-17	57.0	0.87	0.93	0.84	0.85	0.60	0.56
IRAS00275-00	0:30: 9.09	-0:27:44.40	2005-07-08	47.2	2.33	2.16	1.88	1.70	...	...
IRAS00275-28	0:30: 4.20	-28:42:25.40	2003-12-17	28.6	0.87	0.92	0.80	0.81	...	...
IRAS00397-13	0:42:15.50	-12:56: 3.50	2004-01-04	57.0	0.97	0.97	0.90	0.92	0.70	0.54
IRAS00406-31	0:43: 3.14	-31:10:49.70	2005-07-11	47.2	0.95	0.99	0.93	0.94	...	...
IRAS00476-00	0:50: 9.81	-0:39: 1.00	2004-07-18	67.8	0.82	0.84	0.75	0.69	...	0.19
IRAS01003-22	1: 2:49.94	-22:21:57.30	2004-01-04	44.3	0.96	1.04	0.85	0.82	0.87	0.70
IRAS01199-23	1:22:20.84	-22:51:57.30	2004-07-18	30.4	1.08	1.16	0.96	0.92	...	...
IRAS02115+02	2:14:10.32	2:39:59.80	2005-02-07	23.7	0.18	0.74	0.66	0.75	...	...
IRAS02433+01	2:45:55.36	1:23:28.40	2005-01-12	43.0	1.00	1.00	0.99	0.98	...	...
IRAS03521+00	3:54:42.15	0:37: 2.00	2004-02-27	57.2	0.90	0.90	0.80	0.81	0.42	0.48
IRAS04114-51	4:12:44.92	-51: 9:34.20	2004-08-11	28.5	0.98	1.02	0.97	1.02	...	...
IRAS04313-16	4:33:37.08	-16:43:31.50	2004-03-01	35.8	0.94	1.14	0.91	0.92	...	...
IRAS05189-25	5:21: 1.41	-25:21:45.50	2004-03-22	41.2	1.05	1.09	1.00	1.01	1.07	1.07
IRAS06035-71	6: 2:53.63	-71: 3:11.90	2004-04-14	42.9	1.37	1.47	1.17	1.07	1.73	1.07
IRAS06206-63	6:21: 0.80	-63:17:23.20	2004-04-16	44.1	0.91	0.96	0.84	0.78	1.05	0.79
IRAS06301-79	6:26:42.20	-79:36:30.40	2004-08-11	28.5	1.00	1.09	0.92	0.95	...	...
IRAS06361-62	6:36:35.71	-62:20:31.80	2004-08-11	30.4	0.94	0.97	0.96	0.98	...	...
IRAS07598+65	8: 4:30.46	64:59:52.90	2004-02-29	43.2	1.08	1.11	1.01	0.98	1.05	0.92
IRAS08311-24	8:33:20.47	-25: 9:33.10	2004-04-14	42.9	...	...	...	...	1.68	1.16
IRAS08572+39	9: 0:25.38	39: 3:54.30	2004-04-15	42.3	1.05	1.13	1.00	0.91	1.05	0.89
IRAS09022-36	9: 4:12.69	-36:27: 1.70	2005-06-07	37.8	...	...	...	...	...	...
IRAS09463+81	9:53: 0.09	81:27:28.20	2004-03-23	28.5	1.27	1.29	0.94	0.95	...	...
IRAS10091+47	10:12:16.74	46:49:42.90	2004-04-19	28.5	0.87	0.88	0.84	0.85	...	...
IRAS10398+32	10:42:40.81	32:31:31.00	2004-12-08	42.9	0.85	0.81	0.02	0.76	...	...

Table 2—Continued

Object	RA	Dec	Date Obs.	Exec. Time (min)	Scale Factor to IRAS 25 μm flux density					
	(J2000)	(J2000)			SL2	SL1	LL2	LL1	SH	LH
IRAS10565+24	10:59:18.14	24:32:34.30	2004-05-12	42.8	1.22	1.32	1.11	1.03	1.12	0.97
IRAS11119+32	11:14:38.88	32:41:33.10	2004-05-11	52.0	1.20	1.57	1.00	1.01	1.10	0.86
IRAS12018+19	12: 4:24.53	19:25: 9.80	2004-05-15	51.9	1.06	1.10	0.92	0.92	0.87	0.76
IRAS12032+17	12: 5:47.73	16:51: 8.20	2004-01-04	28.6	1.22	1.27	1.00	0.95	...	...
IRAS12072-04	12: 9:45.12	-5: 1:13.90	2004-01-06	44.3	1.16	1.23	1.11	1.12	0.99	0.88
IRAS12112+03	12:13:46.05	2:48:41.30	2004-01-04	44.0	1.33	1.37	1.24	1.25	1.12	0.93
IRAS12514+10	12:54: 0.82	10:11:12.40	2005-02-06	62.7	0.96	0.98	0.92	0.91	0.77	0.60
IRAS13120-54	13:15: 6.40	-55: 9:23.30	2004-03-02	40.1	1.38	1.49	1.07	1.02	1.24	1.09
IRAS13218+05	13:24:19.81	5:37: 4.60	2004-07-17	51.7	0.97	0.99	0.91	0.91	...	0.60
IRAS13342+39	13:36:24.07	39:17:30.10	2004-05-12	64.1	1.07	1.07	0.97	0.94	...	0.88
IRAS13352+64	13:36:51.15	63:47: 4.70	2005-03-20	47.2	0.99	0.96	0.94	0.94	...	...
IRAS13451+12	13:47:33.36	12:17:24.20	2004-01-07	42.9	1.21	1.29	1.19	1.21	1.11	1.02
IRAS14348-14	14:37:38.27	-15: 0:24.60	2004-02-07	44.4	1.07	1.25	1.17	1.13	0.99	0.81
IRAS14378-36	14:40:58.90	-37: 4:33.00	2004-03-02	43.2	1.70	1.51	1.25	1.19	1.62	1.02
IRAS14537+19	14:56: 4.43	19:38:45.70	2004-07-14	67.5	0.85	0.85	0.77	0.74	...	0.22
IRAS14548+33	14:56:58.43	33:37:10.00	2005-03-17	43.1	0.63	0.96	0.91	0.84	...	...
IRAS15001+14	15: 2:31.94	14:21:35.30	2004-06-27	56.9	1.09	1.25	0.96	0.95	...	0.79
IRAS15206+33	15:22:38.12	33:31:36.10	2004-06-24	51.8	1.01	1.07	0.83	0.83	...	0.78
IRAS15250+36	15:26:59.40	35:58:37.50	2004-03-04	43.4	1.03	1.00	0.97	0.92	1.01	0.92
IRAS15462-04	15:48:56.80	-4:59:33.70	2004-03-02	52.1	1.23	1.35	1.04	1.00	0.96	0.83
IRAS16124+32	16:14:22.11	32:34: 3.70	2005-03-19	48.0	0.41	0.92	0.88	0.87	...	...
IRAS16334+46	16:34:52.37	46:24:53.00	2004-03-04	28.8	0.83	0.35	0.65	0.63	...	...
IRAS17068+40	17: 8:32.12	40:23:28.20	2004-04-16	30.4	0.89	0.90	0.90	0.93	...	...
IRAS17179+54	17:18:54.23	54:41:47.30	2004-04-17	66.6	1.14	1.25	1.08	1.04	1.18	1.07
IRAS17208-00	17:23:21.93	-0:17: 0.40	2004-03-27	42.2	1.33	1.35	1.17	1.07	1.19	1.03
IRAS17233+37	17:25: 7.40	37: 9:32.10	2004-06-06	67.6	0.25	1.12	1.12	0.95	...	0.94
IRAS17463+58	17:47: 4.76	58: 5:22.10	2004-04-17	32.8	0.96	0.96	0.91	0.92	...	...

Table 2—Continued

Object	RA	Dec	Date Obs.	Exec. Time (min)	Scale Factor to IRAS 25 μ m flux density					
	(J2000)	(J2000)			SL2	SL1	LL2	LL1	SH	LH
IRAS18030+07	18: 5:32.50	7: 6: 9.00	2004-03-25	28.5	0.87	0.93	0.78	0.75	...	...
IRAS18443+74	18:42:54.80	74:36:21.00	2004-03-05	30.7	1.01	0.97	0.94	0.95	...	...
IRAS19254-72	19:31:21.55	-72:39:22.00	2005-05-30	37.7	...	...	...	...	6.62	1.31
IRAS19297-04	19:32:21.25	-3:59:56.30	2004-05-13	42.7	0.95	0.97	0.84	0.82	...	0.71
IRAS19458+09	19:48:15.70	9:52: 5.00	2004-04-18	30.4	1.15	1.14	1.05	0.96	...	...
IRAS20037-15	20: 6:31.70	-15:39: 8.00	2004-04-18	28.5	1.16	1.26	0.96	0.94	...	...
IRAS20087-03	20:11:23.86	-2:59:50.80	2004-05-14	49.1	0.99	0.96	0.87	0.86	...	0.62
IRAS20100-41	20:13:29.85	-41:47:34.70	2004-04-13	44.1	0.89	0.90	0.86	0.82	0.70	0.70
IRAS20414-16	20:44:18.18	-16:40:16.40	2004-05-14	44.1	1.06	1.07	0.88	0.83	...	0.55
IRAS20551-42	20:58:26.78	-42:39: 1.60	2004-05-14	39.7	1.07	1.11	0.97	0.92	...	0.85
IRAS21272+25	21:29:29.40	25:27:55.10	2004-06-24	30.4	1.16	1.18	1.12	1.13	...	...
IRAS22491-18	22:51:49.35	-17:52:24.00	2004-06-24	44.2	1.37	1.38	1.11	1.11	...	0.99
IRAS23128-59	23:15:47.01	-59: 3:16.90	2004-05-11	42.4	1.59	1.73	1.43	1.38	...	1.11
IRAS23129+25	23:15:21.41	26: 4:32.60	2003-12-17	40.6	0.92	0.92	0.92	0.91	...	...
IRAS23365+36	23:39: 1.29	36:21: 9.80	2004-01-08	43.1	2.90	2.68	1.31	1.17	2.33	1.08
IRAS23498+24	23:52:26.05	24:40:16.20	2004-01-04	64.1	0.97	1.03	0.81	0.84	0.68	0.53
IRAS23529-21	23:55:33.22	-21: 2:59.60	2003-12-16	40.6	1.00	0.99	0.87	0.82	...	...
Mrk1014	1:59:50.23	0:23:40.50	2004-01-07	43.0	1.17	1.32	1.09	1.04	1.08	0.86
Mrk231	12:56:14.29	56:52:25.10	2004-04-14	41.0	1.20	1.17	1.03	1.03	1.18	1.09
Mrk273	13:44:42.12	55:53:13.10	2004-04-14	39.8	1.18	1.19	1.06	1.06	1.24	1.07
Mrk463E	13:56: 2.90	18:22:19.00	2004-01-07	42.5	1.00	1.02	0.97	1.01	0.99	0.97
NGC6240	16:52:58.89	2:24: 3.40	2004-03-04	40.0	0.93	1.08	1.00	1.01	1.10	1.03
UGC5101	9:35:51.65	61:21:11.30	2004-03-23	42.7	1.11	1.19	1.13	1.15	1.19	1.10

Table 3. Measured Line Fluxes and Limits

Object	S(0) 28.22 μm (10^{-20} W cm $^{-2}$)	S(1) 17.04 μm (10^{-20} W cm $^{-2}$)	S(2) 12.28 μm (10^{-20} W cm $^{-2}$)	S(3) 9.67 μm (10^{-20} W cm $^{-2}$)	S(7) 5.51 μm (10^{-20} W cm $^{-2}$)	L_{H_2}/L_{IR}^a (%)
3C273	< 2.2	<3.5	<3.2	<3.6	<27.3	...
Arp220	<97.0	$1.862^{+0.168}_{-0.168}$	$0.98^{+0.13}_{-0.13}$	$0.73^{+0.02b}_{-0.02b}$	$1.29^{+0.38}_{-0.38}$	0.006
IRAS 00188-0856	< 1.9	$0.043^{+0.005}_{-0.005}$	$0.020^{+0.004}_{-0.004}$	$0.038^{+0.012}_{-0.012}$	<3.2	0.004
IRAS 00275-0044	< 3.7 ^b	<1.2 ^b	<1.1 ^b	<0.5 ^b	<0.8	...
IRAS 00275-2859	< 5.4 ^b	<3.1 ^b	<2.6 ^b	<2.7 ^b	<3.0	...
IRAS 00397-1312	< 1.6	$0.029^{+0.004}_{-0.004}$	$0.017^{+0.002}_{-0.002}$	$0.023^{+0.006}_{-0.006}$	<8.0	0.006
IRAS 00406-3127	< 5.1 ^b	<1.5 ^b	<1.2 ^b	$0.019^{+0.001b}_{-0.001b}$	<1.0	0.003
IRAS 00476-0054	...	<0.1	<0.4 ^b	<0.3 ^b	<0.2	...
IRAS 01003-2238	< 3.5	$0.087^{+0.031}_{-0.031}$	$0.034^{+0.002}_{-0.002}$	$0.057^{+0.007}_{-0.007}$	<2.5	0.008
IRAS 01199-2307	<10.6 ^b	<1.5 ^b	<1.2 ^b	<0.1 ^b	<0.5	...
IRAS 02115+0226	...	<0.2 ^b	<0.2 ^b	$0.029^{+0.002b}_{-0.002b}$	<0.03	0.004
IRAS 02433+0110	...	<1.0 ^b	<0.8 ^b	<0.6 ^b	<0.4	...
IRAS 03521+0028	< 1.3	$0.082^{+0.013}_{-0.013}$	$0.027^{+0.009}_{-0.009}$	$0.037^{+0.003}_{-0.003}$	<0.3	0.006
IRAS 04114-5117	< 8.7 ^b	$0.104^{+0.010b}_{-0.010b}$	<0.6 ^b	$0.051^{+0.019b}_{-0.019b}$	<0.4	0.009
IRAS 04313-1649	< 6.6 ^b	<0.9 ^b	<0.5 ^b	<0.1 ^b	<0.2	...
IRAS 05189-2524	<28.2	$0.34^{+0.07}_{-0.07}$	$0.15^{+0.02}_{-0.02}$	$0.36^{+0.13}_{-0.13}$	<34.1	0.003
IRAS 06035-7102	< 6.1	$0.417^{+0.004}_{-0.004}$	$0.233^{+0.058}_{-0.058}$	$0.34^{+0.10}_{-0.10}$	<11.6	0.023
IRAS 06206-6315	< 2.9	$0.129^{+0.010}_{-0.010}$	$0.050^{+0.005}_{-0.005}$	$0.059^{+0.019}_{-0.019}$	<1.8	0.008
IRAS 06301-7934	< 9.6 ^b	$0.107^{+0.020b}_{-0.020b}$	$0.044^{+0.016b}_{-0.016b}$	$0.072^{+0.017b}_{-0.017b}$	$0.095^{+0.018}_{-0.018}$	0.022
IRAS 06361-6217	<14.0 ^b	$0.094^{+0.004b}_{-0.004b}$	<2.1 ^b	<0.3 ^b	<2.3	0.011
IRAS 07598+6508	< 3.0	$0.138^{+0.070}_{-0.070}$	$0.037^{+0.006}_{-0.006}$	$0.067^{+0.002}_{-0.002}$	<22.5	0.011
IRAS 08311-2459	< 7.5	$0.388^{+0.030}_{-0.030}$	$0.252^{+0.026}_{-0.026}$	$0.32^{+0.10}_{-0.10}$	<2.6	0.019
IRAS 08572+3915	<15.4	$0.119^{+0.004}_{-0.004}$	$0.051^{+0.010}_{-0.010}$	$0.046^{+0.013}_{-0.013}$	<43.0	0.003
IRAS 09022-3615 ^c	< 3.3	$0.122^{+0.008}_{-0.008}$	<0.2	<0.2	<0.04	0.001
IRAS 09463+8141	< 4.4 ^b	$0.108^{+0.055b}_{-0.055b}$	$0.045^{+0.022b}_{-0.022b}$	$0.083^{+0.007b}_{-0.007b}$	<0.4	0.019
IRAS 10091+4704	< 4.5 ^b	<0.4 ^b	<0.4 ^b	<0.1 ^b	<0.3	...
IRAS 10398+3247	...	<0.1 ^b	<0.001 ^b	<0.004 ^b	<0.2	...
IRAS 10565+2448	<10.9	$0.657^{+0.005}_{-0.005}$	$0.256^{+0.009}_{-0.009}$	$0.403^{+0.002}_{-0.002}$	<5.4	0.013
IRAS 11119+3257	< 2.5	<1.7	<1.6	$0.054^{+0.007}_{-0.007}$	<9.1	0.003
IRAS 12018+1941	< 2.6	$0.093^{+0.006}_{-0.006}$	$0.030^{+0.003}_{-0.003}$	$0.043^{+0.008}_{-0.008}$	<1.1	0.010
IRAS 12032+1707	<10.7 ^b	$0.094^{+0.030b}_{-0.030b}$	<1.5 ^b	$0.077^{+0.027b}_{-0.027b}$	$0.147^{+0.044}_{-0.044}$	0.028
IRAS 12072-0444	< 4.5	$0.192^{+0.017}_{-0.017}$	$0.089^{+0.010}_{-0.010}$	$0.136^{+0.008}_{-0.008}$	<2.7	0.020
IRAS 12112+0305	$0.14^{+0.04}_{-0.04}$	$0.412^{+0.044}_{-0.044}$	$0.173^{+0.031}_{-0.031}$	$0.237^{+0.003}_{-0.003}$	$0.41^{+0.08}_{-0.08}$	0.021
IRAS 12514+1027	< 0.7	<0.5	<0.5	<0.2	<4.0	...
IRAS 13120-5453	<30.9	$1.047^{+0.034}_{-0.034}$	$0.662^{+0.045}_{-0.045}$	$0.763^{+0.005}_{-0.005}$	<14.6	0.008
IRAS 13218+0552	< 1.8	<1.5	<8.9 ^b	<9.4 ^b	<16.9	...
IRAS 13342+3932	$0.03^{+0.01}_{-0.01}$	$0.102^{+0.002}_{-0.002}$	<3.9 ^b	<4.2 ^b	<2.6	0.016
IRAS 13352+6402	< 5.2 ^b	<1.1 ^b	<0.9 ^b	$0.016^{+0.008b}_{-0.008b}$	<1.2	0.002
IRAS 13451+1232	< 4.5	$0.283^{+0.065}_{-0.065}$	$0.129^{+0.005}_{-0.005}$	$0.219^{+0.026}_{-0.026}$	<4.1	0.031
IRAS 14348-1447	< 6.1	$0.447^{+0.015}_{-0.015}$	$0.195^{+0.010}_{-0.010}$	$0.240^{+0.021}_{-0.021}$	<3.1	0.017
IRAS 14378-3651	< 6.6	$0.193^{+0.016}_{-0.016}$	$0.079^{+0.016}_{-0.016}$	$0.125^{+0.180}_{-0.180}$	<2.3	0.008
IRAS 14537+1950	...	<0.1	<0.2 ^b	<0.1 ^b	<0.1	...
IRAS 14548+3349	...	<0.2 ^b	<0.2 ^b	<0.1 ^b	<0.2	...
IRAS 15001+1433	< 1.9	$0.077^{+0.007}_{-0.007}$	<2.8 ^b	$0.068^{+0.013b}_{-0.013b}$	<1.7	0.010
IRAS 15206+3342	< 2.5	$0.102^{+0.053b}_{-0.053b}$	<4.3 ^b	<2.6 ^b	<1.6	0.006

Table 3—Continued

Object	S(0) 28.22 μm (10^{-20} W cm $^{-2}$)	S(1) 17.04 μm (10^{-20} W cm $^{-2}$)	S(2) 12.28 μm (10^{-20} W cm $^{-2}$)	S(3) 9.67 μm (10^{-20} W cm $^{-2}$)	S(7) 5.51 μm (10^{-20} W cm $^{-2}$)	L _{H₂} /L _{IR} ^a (%)
IRAS 15250+3609	<12.9	0.156 $^{+0.014}$	0.050 $^{+0.006}$	0.048 $^{+0.004}$	<10.4	0.004
IRAS 15462-0450	< 4.1	0.134 $^{+0.006}$	0.037 $^{+0.001}$	0.086 $^{+0.012}$	<5.7	0.010
IRAS 16124+3241	...	<0.3 ^b	<0.1 ^b	<0.1 ^b	<0.1	...
IRAS 16334+4630	< 4.2 ^b	<0.9 ^b	<0.7 ^b	<0.4 ^b	<0.4	...
IRAS 17068+4027	<10.2 ^b	0.072 $^{+0.018}$ ^b	<1.7 ^b	0.052 $^{+0.017}$ ^b	0.087 $^{+0.019}$	0.020
IRAS 17179+5444	< 1.7	0.209 $^{+0.007}$	0.068 $^{+0.024}$	0.14 $^{+0.02}$	<1.4	0.031
IRAS 17208-0014	<23.9	0.881 $^{+0.009}$	0.497 $^{+0.085}$	0.57 $^{+0.11}$	<8.5	0.009
IRAS 17233+3712	...	<0.1	<0.5 ^b	<0.3 ^b	<0.1	...
IRAS 17463+5806	< 3.5 ^b	<0.6 ^b	<0.3 ^b	0.023 $^{+0.011}$ ^b	<0.2	0.007
IRAS 18030+0705	< 1.4 ^b	0.111 $^{+0.008}$ ^b	<0.8 ^b	<0.4 ^b	<0.2	0.008
IRAS 18443+7433	<15.5 ^b	<2.7 ^b	<2.4 ^b	0.048 $^{+0.007}$ ^b	<1.7	0.003
IRAS 19254-7245	< 8.5	0.881 $^{+0.057}$	0.382 $^{+0.095}$	0.382 $^{+0.004}$	<0.4	0.031
IRAS 19297-0406	< 4.8	0.332 $^{+0.082}$ ^b	<3.3 ^b	0.196 $^{+0.008}$ ^b	<1.7	0.009
IRAS 19458+0944	<19.3 ^b	0.219 $^{+0.042}$ ^b	<2.2 ^b	0.113 $^{+0.038}$ ^b	<1.0	0.009
IRAS 20037-1547	<11.2 ^b	<5.8 ^b	<4.4 ^b	0.081 $^{+0.005}$ ^b	<4.8	0.006
IRAS 20087-0308	< 2.1	0.229 $^{+0.014}$ ^b	0.084 $^{+0.033}$ ^b	0.13 $^{+0.04}$ ^b	<2.2	0.011
IRAS 20100-4156	< 4.6	0.083 $^{+0.007}$	0.032 $^{+0.001}$	0.068 $^{+0.010}$	<2.9	0.005
IRAS 20414-1651	< 2.4	0.156 $^{+0.003}$ ^b	<1.6 ^b	0.049 $^{+0.033}$ ^b	<0.7	0.006
IRAS 20551-4250	<16.3	0.896 $^{+0.052}$ ^b	<18.0 ^b	0.443 $^{+0.020}$ ^b	<9.8	0.013
IRAS 21272+2514	< 6.6 ^b	<1.0 ^b	<0.7 ^b	0.037 $^{+0.002}$ ^b	<0.5	0.004
IRAS 22491-1808	< 7.0	0.165 $^{+0.005}$ ^b	<3.1 ^b	0.098 $^{+0.013}$ ^b	<1.0	0.006
IRAS 23128-5919	<12.2	0.514 $^{+0.010}$ ^b	<22.595 ^b	0.305 $^{+0.080}$ ^b	<7.3	0.009
IRAS 23129+2548	<10.1 ^b	<1.3 ^b	<1.1 ^b	<0.1 ^b	<0.6	...
IRAS 23365+3604	< 9.1	0.390 $^{+0.031}$	0.201 $^{+0.095}$	0.31 $^{+0.05}$	<3.0	0.015
IRAS 23498+2423	<0.68	<0.5	<0.3	<0.2	<2.1	...
IRAS 23529-2119	...	<1.4 ^b	<1.0 ^b	0.028 $^{+0.011}$ ^b	<0.7	0.010
Mrk 231 ^d	<67.5	<31.7	<26.8	0.46 $^{+0.13}$	<122.3	0.001
Mrk 273	<26.25	1.024 $^{+0.009}$	0.56 $^{+0.07}$	1.04 $^{+0.09}$	<15.0	0.015
Mrk 463E	< 7.9	0.279 $^{+0.037}$	0.131 $^{+0.008}$	0.28 $^{+0.06}$	<38.5	0.017
Mrk 1014	< 4.2	<2.5	<1.5	0.07 $^{+0.03}$	<4.6	0.003
NGC 6240	0.50 $^{+0.25}$	4.271 $^{+0.344}$	3.55 $^{+0.26}$	5.83 $^{+0.43}$	5.54 $^{+0.50}$	0.097
UGC 5101	<10.0	0.496 $^{+0.047}$	0.27 $^{+0.05}$	0.28 $^{+0.03}$	<19.5	0.010

^aRatio of the sum of the H₂ line fluxes divided by the IR luminosity in %. The far-infrared luminosities are defined in Table 2.

^bEmission lines observed using IRS-LORES.

^cThe absolute flux calibration for IRAS 09022-3615 is uncertain, see text

^dBoth the S(1) and S(2) lines are present. However we quote upper limits as both lines are poorly calibrated. The S(1) line straddles orders 12 and 11 in IRS-SH and the centre of S(2) line profile is affected by bad pixel values.

Table 4. Properties of the Warm Molecular H₂

Object	T _{ex} (K)	Warm M _{H₂} (10 ⁷ M _⊙)	Cold M _{H₂} (10 ¹⁰ M _⊙)	$\frac{\text{Warm M}_{\text{H}_2}}{\text{Cold M}_{\text{H}_2}}$ (%)
Arp 220	1435 [±] 20 258 [±] 4	0.03 [±] 0.02 6.6 [±] 0.8		
			3.72 ^{R1}	0.18
IRAS 00188-0856	358 [±] 25	4.11 [±] 1.18	3.98 ^{R1}	0.10
IRAS 00397-1312	365 [±] 24	13.16 [±] 3.69	...	...
IRAS 00406-3127 ^L	< 336 [±] 15 >	32.04 [±] 11.95	...	...
IRAS 01003-2238	365 [±] 19	6.68 [±] 2.71	...	...
IRAS 02115+0226 ^L	< 336 [±] 15 >	69.14 [±] 26.08	...	...
IRAS 03521+0028	317 [±] 11	14.67 [±] 3.14	5.62 ^{R1}	0.26
IRAS 04114-5117 ^L	321 [±] 26	11.74 [±] 4.05	...	...
IRAS 05189-2524	380 [±] 30	2.86 [±] 1.82	0.26 ^{R2}	1.1
IRAS 06035-7102	363 [±] 23	13.94 [±] 3.30	4.17 ^{R3}	0.33
IRAS 06206-6315	313 [±] 15	8.14 [±] 1.76	9.33 ^{R3}	0.09
IRAS 06301-7934 ^L	1329 [±] 106 264 [±] 14	0.3 [±] 0.1 32 [±] 10	......	......
IRAS 06361-6217 ^L	< 336 [±] 15 >	16.56 [±] 2.93	...	...
IRAS 07598+6508	366 [±] 22	17.53 [±] 9.65	6.76 ^{R1}	0.26
IRAS 08311-2459	384 [±] 22	19.27 [±] 4.23	...	...
IRAS 08572+3915	310 [±] 18	2.93 [±] 0.76	0.72 ^{R3}	0.41
IRAS 09022-3615	< 336 [±] 15 >	2.61 [±] 0.48	...	...
IRAS 09463+8141 ^L	363 [±] 39	15.10 [±] 9.80	...	...
IRAS 10565+2448	338 [±] 1	7.05 [±] 0.10	3.02 ^{R3}	0.23
IRAS 11119+3257	< 336 [±] 15 >	23.21 [±] 9.14	...	...
IRAS 12018+1941	309 [±] 11	22.26 [±] 3.63	...	...
IRAS 12032+1707 ^L	1471 [±] 196 309 [±] 30	0.5 [±] 0.5 38 [±] 20	......	......
IRAS 12072-0444	349 [±] 8	19.32 [±] 2.39	...	...
IRAS 12112+0305	1428 [±] 1049 271 [±] 5	0.2 [±] 0.8 119 [±] 41		
			0.49 ^{R4}	24

Table 4—Continued

Object	T_{ex} (K)	Warm M_{H_2} ($10^7 M_{\odot}$)	Cold M_{H_2} ($10^{10} M_{\odot}$)	$\frac{\text{Warm } M_{\text{H}_2}}{\text{Cold } M_{\text{H}_2}}$ (%)
IRAS 13120-5453	348^{+3}_{-3}	$5.29^{+0.24}_{-0.24}$	...	...
IRAS 13342+3932	141^{+15}_{-15}	803^{+459}_{-459} (s0)	...	...
	$< 336^{+15}_{-15} >$	$23.15^{+0.46}_{-0.46}$	...	...
IRAS 13352+6402 ^L	$< 336^{+15}_{-15} >$	$11.10^{+7.04}_{-7.04}$	...	...
IRAS 13451+1232	366^{+18}_{-18}	$23.30^{+6.85}_{-6.85}$	0.51^{R4}	4.57
IRAS 14348-1447	328^{+6}_{-6}	$19.86^{+1.61}_{-1.61}$	3.47^{R4}	0.57
IRAS 14378-3651	320^{+31}_{-31}	$5.97^{+2.42}_{-2.42}$	2.29^{R3}	0.26
IRAS 15001+1433 ^L	346^{+40}_{-40}	$17.05^{+11.10}_{-11.10}$	...	...
IRAS 15206+3342 ^L	$< 336^{+15}_{-15} >$	$10.45^{+5.72}_{-5.72}$	...	...
IRAS 15250+3609	294^{+7}_{-7}	$3.89^{+0.53}_{-0.53}$	...	...
IRAS 15462-0450	285^{+5}_{-5}	$12.57^{+1.15}_{-1.15}$	...	...
IRAS 17068+4027 ^L	1416^{+154}_{-154}	$0.2^{+0.2}_{-0.2}$	...	...
	292^{+23}_{-23}	22^{+9}_{-9}	...	...
IRAS 17179+5444	340^{+13}_{-13}	$30.03^{+4.61}_{-4.61}$	...	...
IRAS 17208-0014	347^{+13}_{-13}	$8.93^{+1.29}_{-1.29}$	3.80^{R1}	0.23
IRAS 17463+5806 ^L	$< 336^{+15}_{-15} >$	$29.87^{+17.70}_{-17.70}$	...	...
IRAS 18030+0705 ^L	$< 336^{+15}_{-15} >$	$16.01^{+3.00}_{-3.00}$	...	...
IRAS 18443+7433 ^L	$< 336^{+15}_{-15} >$	$9.71^{+3.87}_{-3.87}$	...	...
IRAS 19254-7245	313^{+4}_{-4}	$23.63^{+1.99}_{-1.99}$	4.57^{R6}	0.52
IRAS 19297-0406 ^L	334^{+18}_{-18}	$15.39^{+5.02}_{-5.02}$	5.25^{R1}	0.29
IRAS 19458+0944 ^L	325^{+27}_{-27}	$14.94^{+5.80}_{-5.80}$	6.76^{R1}	0.22
IRAS 20037-1547 ^L	$< 336^{+15}_{-15} >$	$35.92^{+13.50}_{-13.50}$	...	...
IRAS 20087-0308 ^L	326^{+21}_{-21}	$17.49^{+4.69}_{-4.69}$	9.33^{R1}	0.1875
IRAS 20100-4156	339^{+12}_{-12}	$9.05^{+1.46}_{-1.46}$	...	...
IRAS 20414-1651 ^L	294^{+38}_{-38}	$10.04^{+5.70}_{-5.70}$	...	...
IRAS 20551-4250 ^L	322^{+5}_{-5}	$10.46^{+0.90}_{-0.90}$	2.82^{R6}	0.37
IRAS 21272+2514 ^L	$< 336^{+15}_{-15} >$	$9.49^{+3.55}_{-3.55}$	...	...
IRAS 22491-1808 ^L	335^{+10}_{-10}	$6.09^{+0.74}_{-0.74}$	4.27^{R3}	0.14
IRAS 23128-5919 ^L	335^{+19}_{-19}	$6.04^{+1.36}_{-1.36}$	1.95^{R3}	0.31
IRAS 23365+3604	358^{+14}_{-14}	$8.62^{+1.45}_{-1.45}$	4.68^{R1}	0.18

Table 4—Continued

Object	T_{ex} (K)	Warm M_{H_2} ($10^7 M_{\odot}$)	Cold M_{H_2} ($10^{10} M_{\odot}$)	$\frac{\text{Warm } M_{\text{H}_2}}{\text{Cold } M_{\text{H}_2}}$ (%)
IRAS 23529-2119 ^L	$< 336_{-15}^{+15} >$	$81.05_{-43.67}^{+}$	...	...
Mrk 231	$< 336_{-15}^{+15} >$	$7.97_{-3.73}^{+}$	4.07^{R1}	0.20
Mrk 273	378_{-8}^{+}	$6.75_{-0.52}^{+}$	2.69^{R1}	0.25
Mrk 463E	368_{-21}^{+}	$3.50_{-0.87}^{+}$	0.04^{R4}	8.75
Mrk 1014	$< 336_{-15}^{+15} >$	$20.38_{-12.20}^{+}$	5.25^{R1}	0.39
NGC 6240	1327_{-36}^{+} 292_{-6}^{+}	$0.41_{-0.08}^{+}$ 62_{-32}^{+}	4.37^{R1}	1.43
UGC 5101	332_{-11}^{+}	$4.75_{-0.78}^{+}$	0.62^{R2}	0.77

Note. — The Warm Molecular H_2 Mass is derived from our data. HIRES observations are used when available, and the LORES observations are marked in the first column with an ‘L’. The temperature is derived from the fit to the S(1) - S(3) data. The mass is derived using the S(1) line flux, if this line is not detected the S(3) line flux is used. If only a single line is detected we use the average temperature of 336_{-15}^{+15} K to estimate the mass, denoted by ‘<>’ in column 2. The standard Milky Way H_2 mass-to-CO luminosity ratio, $\alpha = 4.6 M_{\odot} / \text{K km s}^{-1} \text{ pc}^2$ has been used to estimate the cold gas mass. The CO references labeled R1-R4 in column 3 are: R1: Solomon et al. 1997; R2: Rigopoulou et al. 1996; R3: Mirabel et al. 1990; R4: Evans et al. 2002. However, Solomon et al. (1997) argue that $\alpha \sim 1.4$ should be used for ULIRGs. This would decrease the cold gas mass and correspondingly increase the warm gas fraction by a factor of ~ 3 . The S(7) line is detected in Arp 220, IRAS 06301-7934, IRAS 12032+1707, IRAS 12112+0305, IRAS 17068+4027 and NGC 6240, and we calculate a hot gas mass. The S(0) line is detected in IRAS 12112+0305, IRAS 13342+3932 and NGC 6240, which lowers the warm gas temperature. The S(0) line flux is used to estimate the gas mass. For IRAS 13342+3932 we only detect the S(0) and S(1) line resulting in much lower gas temperature. We also quote the gas mass using the average temperature for the sample, which may be a more reasonable estimate of the gas mass. There is a problem with the absolute flux calibration for IRAS 09022-3615 and the mass could be a factor twenty higher than quoted.

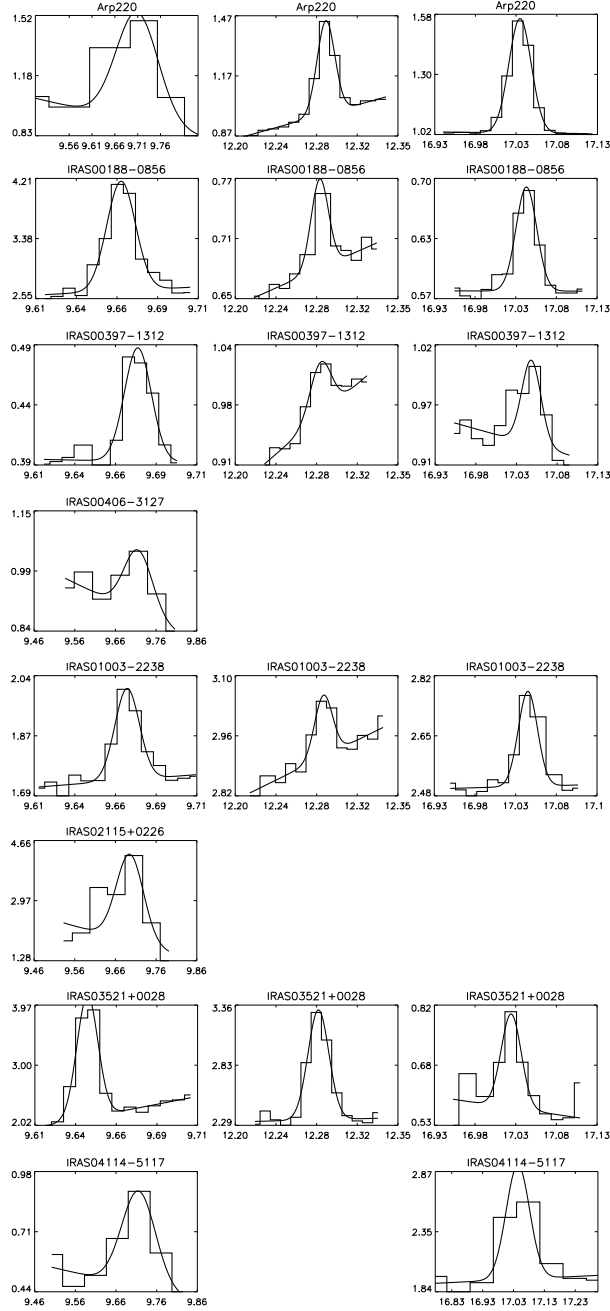


Fig. 1.— Pure rotational H₂ emission lines for the ULIRG sample observed with Spitzer’s IRS. The three columns show (from left to right) the H₂ S(3) 9.67 μm , S(2) 12.28 μm , and S(1) 17.04 μm lines after averaging over both slit positions. The data are shown as a histogram, while the solid line shows a single gaussian plus linear baseline fit. The vertical axis shows flux density in units of $10^{-18} \text{ W cm}^{-2} \mu\text{m}^{-1}$, with rest wavelength in microns shown on the horizontal axis.

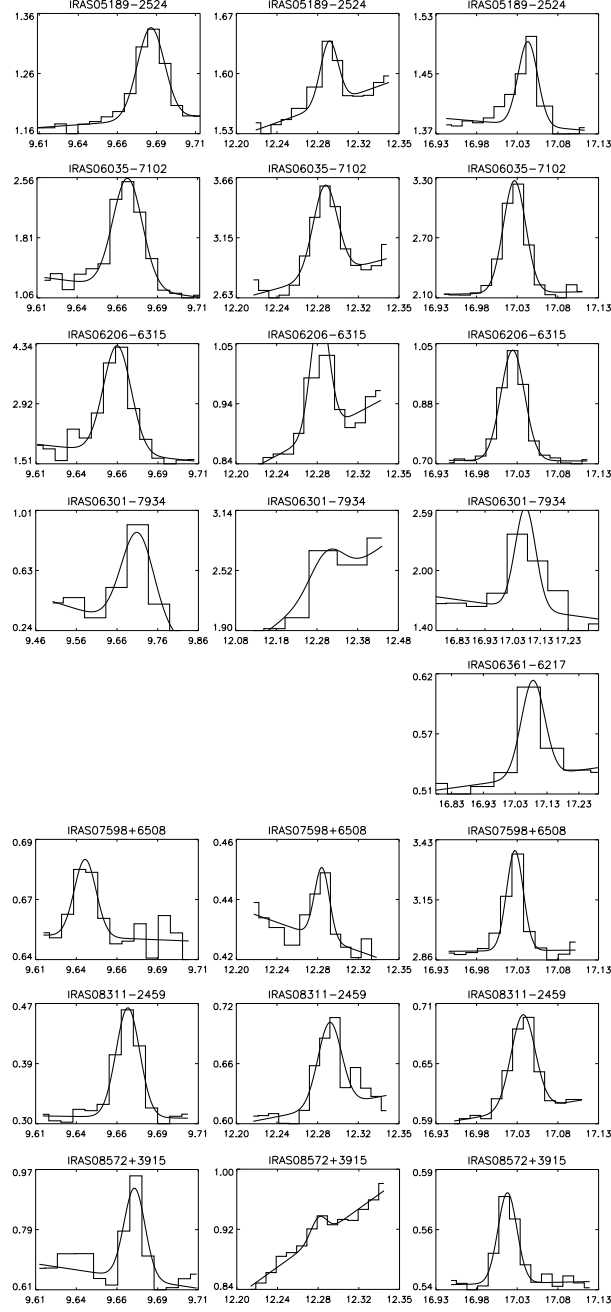


Fig. 1.— Cont.

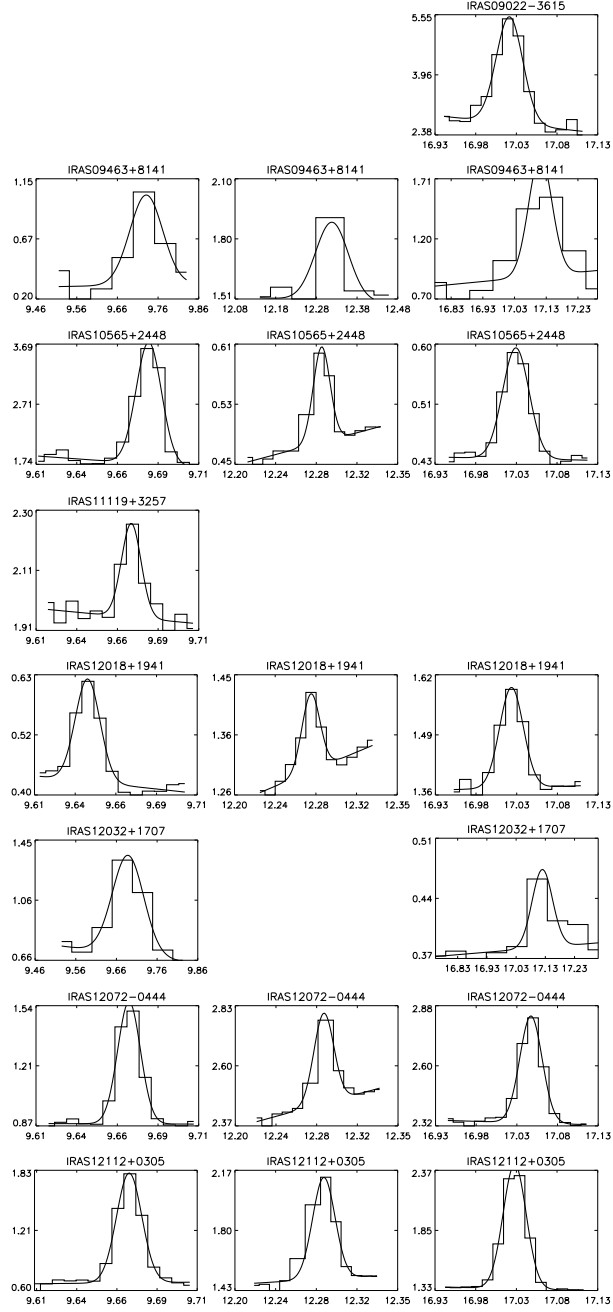


Fig. 1.— Cont.

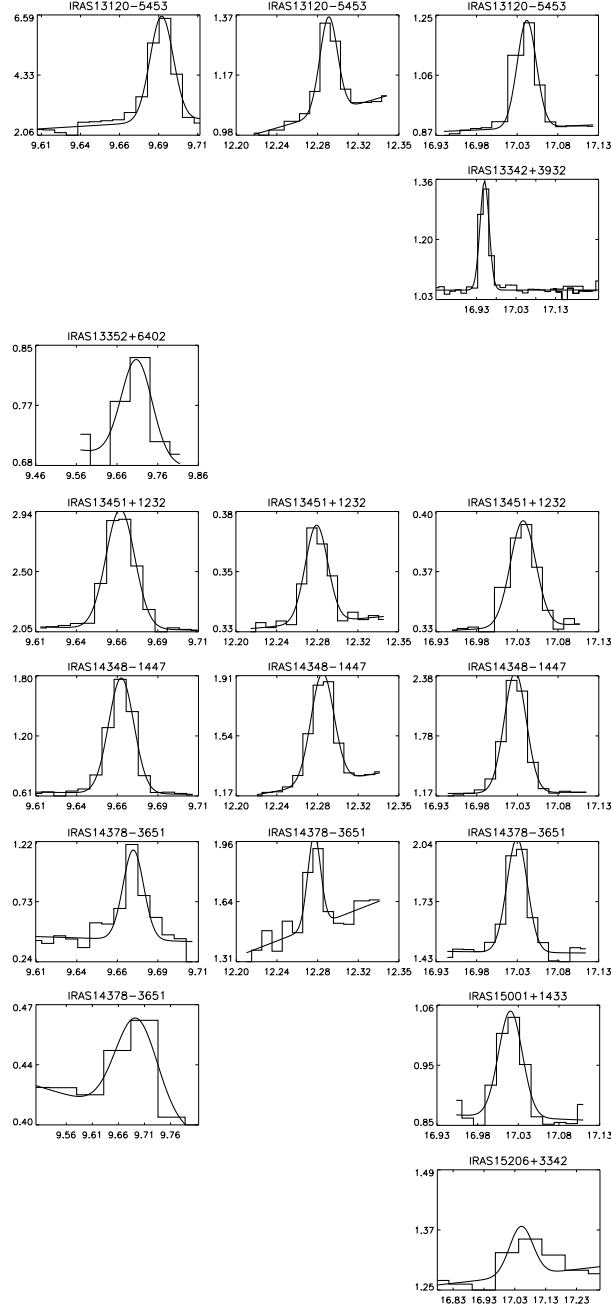


Fig. 1.— Cont.

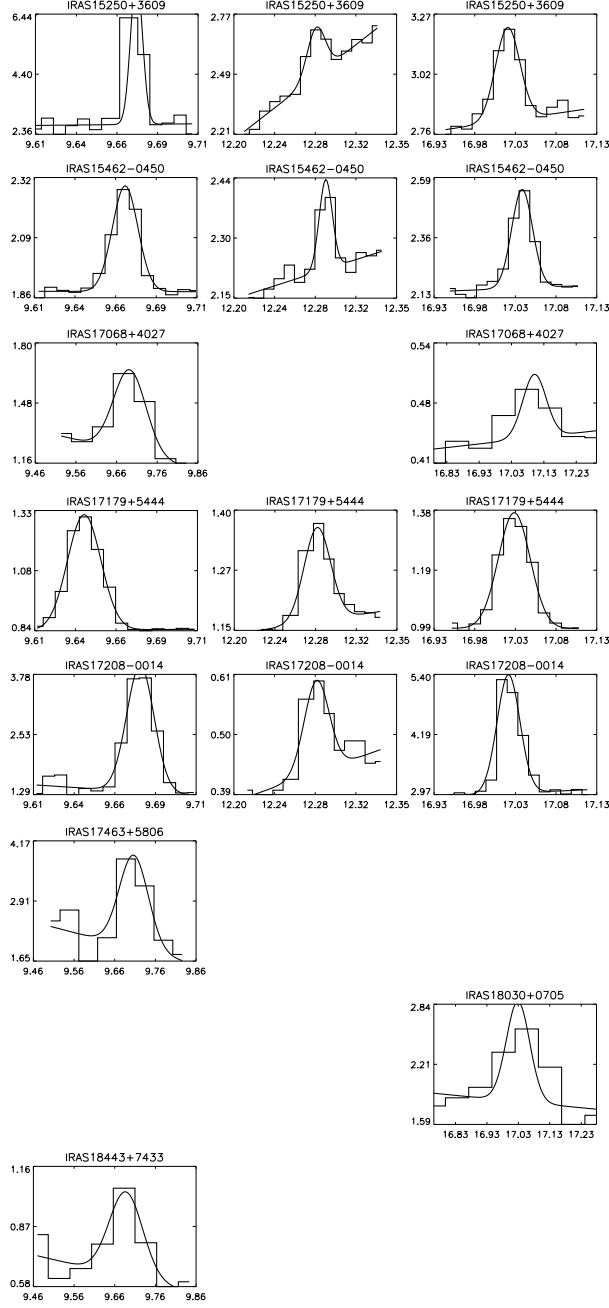


Fig. 1.— Cont.

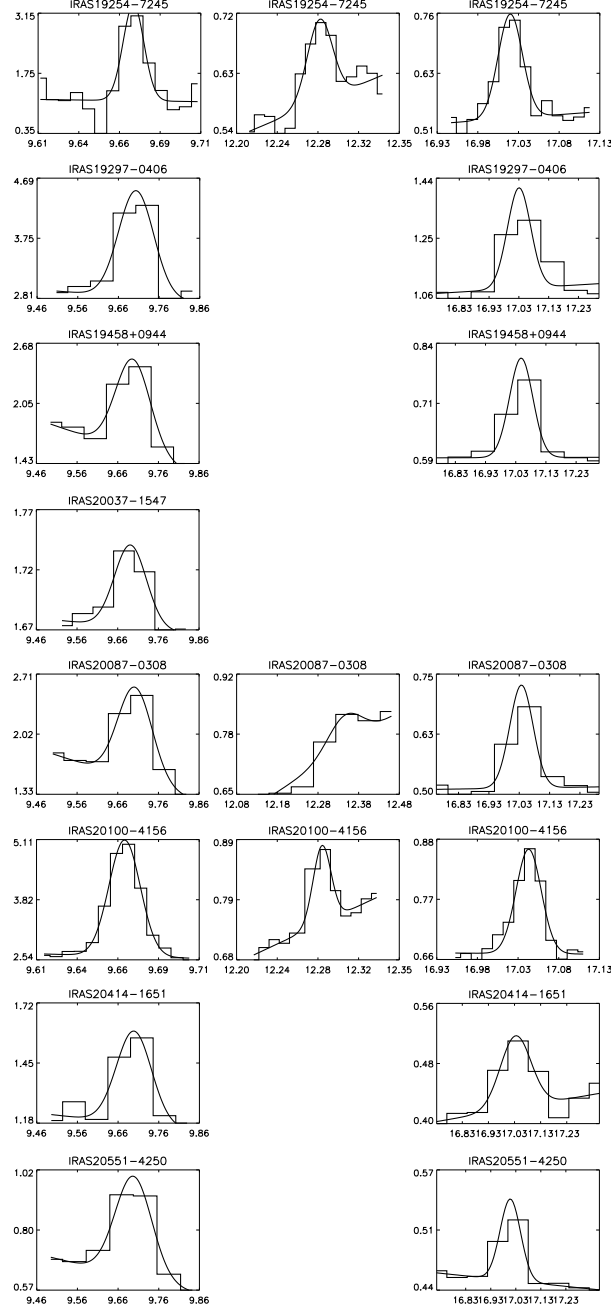


Fig. 1.— Cont.

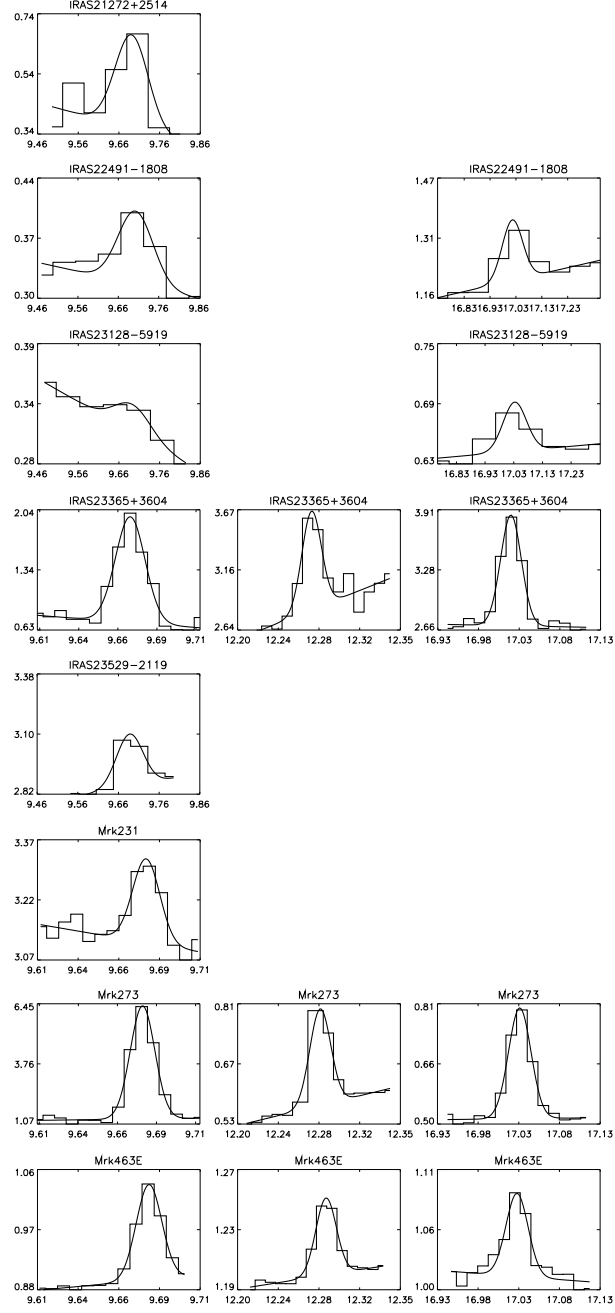


Fig. 1.— Cont.

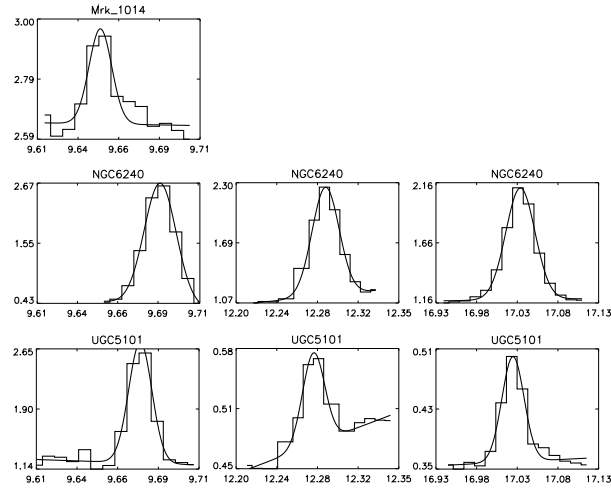


Fig. 1.— Cont.

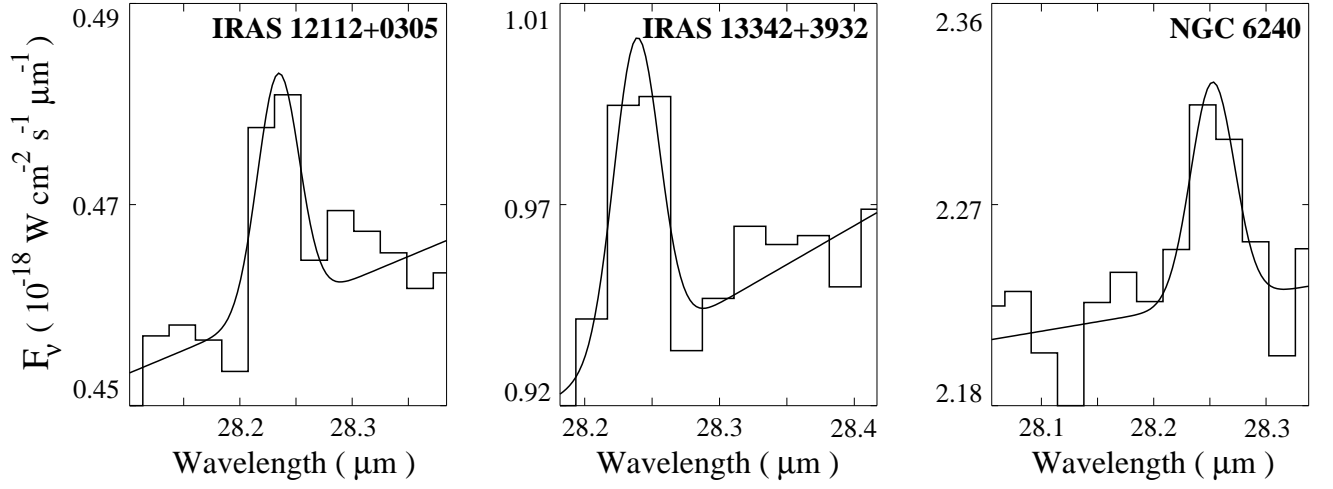


Fig. 2.— Observed (histogram) and fitted (line) H₂ S(0) 28.22 μm lines detected with the IRS in the ULIRGs IRAS 12112+0305, IRAS 13342+3932, and NGC 6240. The spectra represent averages of the two slit positions. The vertical axis shows flux density in units of $10^{-18} \text{ W cm}^{-2} \text{ s}^{-1} \mu\text{m}^{-1}$, while the horizontal axis shows the rest wavelength in microns.

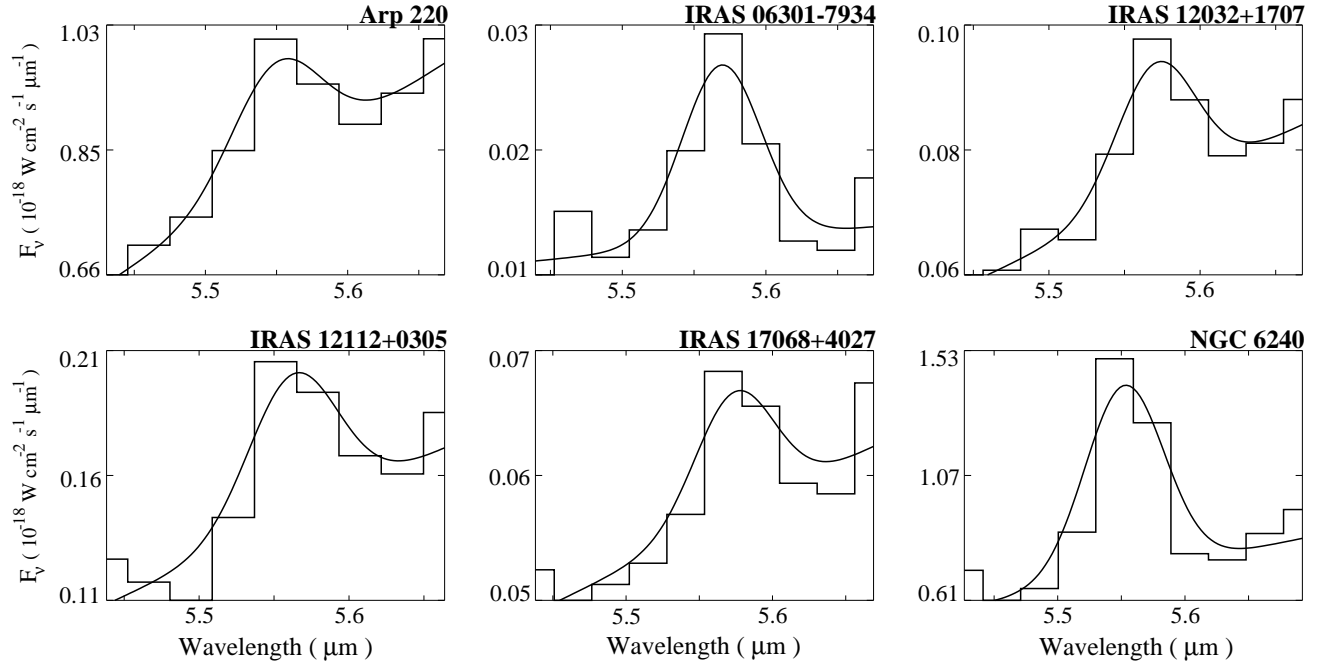


Fig. 3.— Observed (histogram) and fitted (line) H_2 S(7) 5.51 μm emission lines detected with the IRS in the ULIRGs Arp 220, IRAS 06301-79304, IRAS 12032+1707, IRAS 12112+0305, IRAS 17068+4027, and NGC 6240. The spectra represent averages of both slit positions. The vertical axis shows flux density in units of $10^{-18} \text{ W cm}^{-2} \mu\text{m}^{-1}$. Rest wavelength in microns is shown along the horizontal axis.

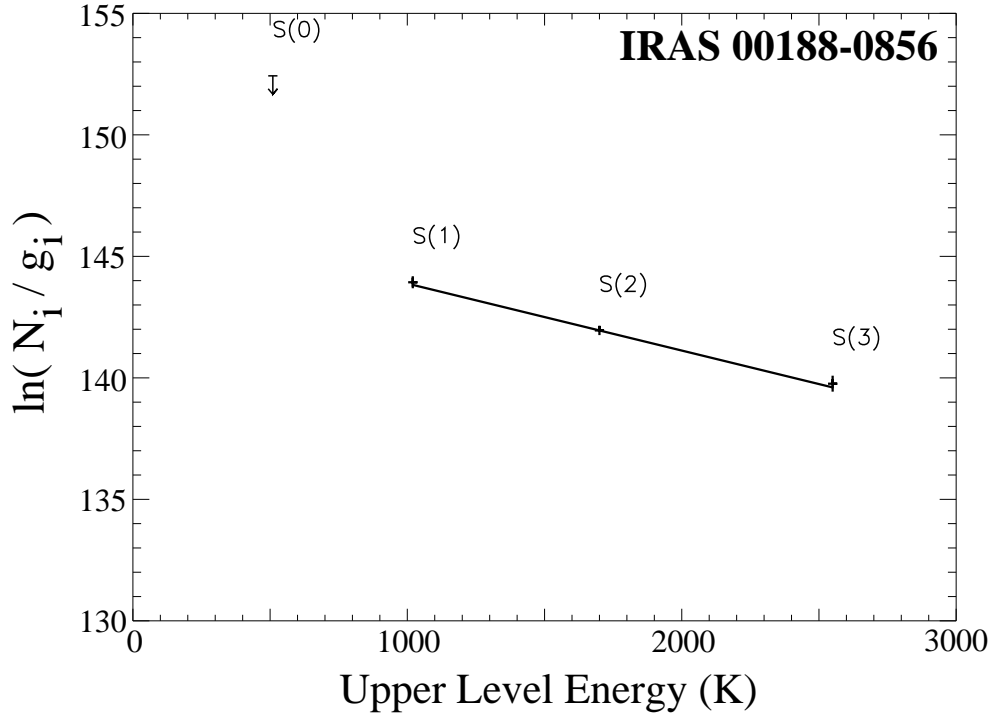


Fig. 4.— Molecular hydrogen excitation diagram for IRAS 00188-0856, which is typical for our ULIRG sample. The solid line shows a fit to the S(1), S(2), and S(3) measurements, which is consistent with a single temperature component at $T_{\text{ex}} = 358 \pm 25$ K, with a mass of $4.1 \times 10^7 M_{\odot}$. The arrow shows the 3σ upper-limit for the S(0) transition.

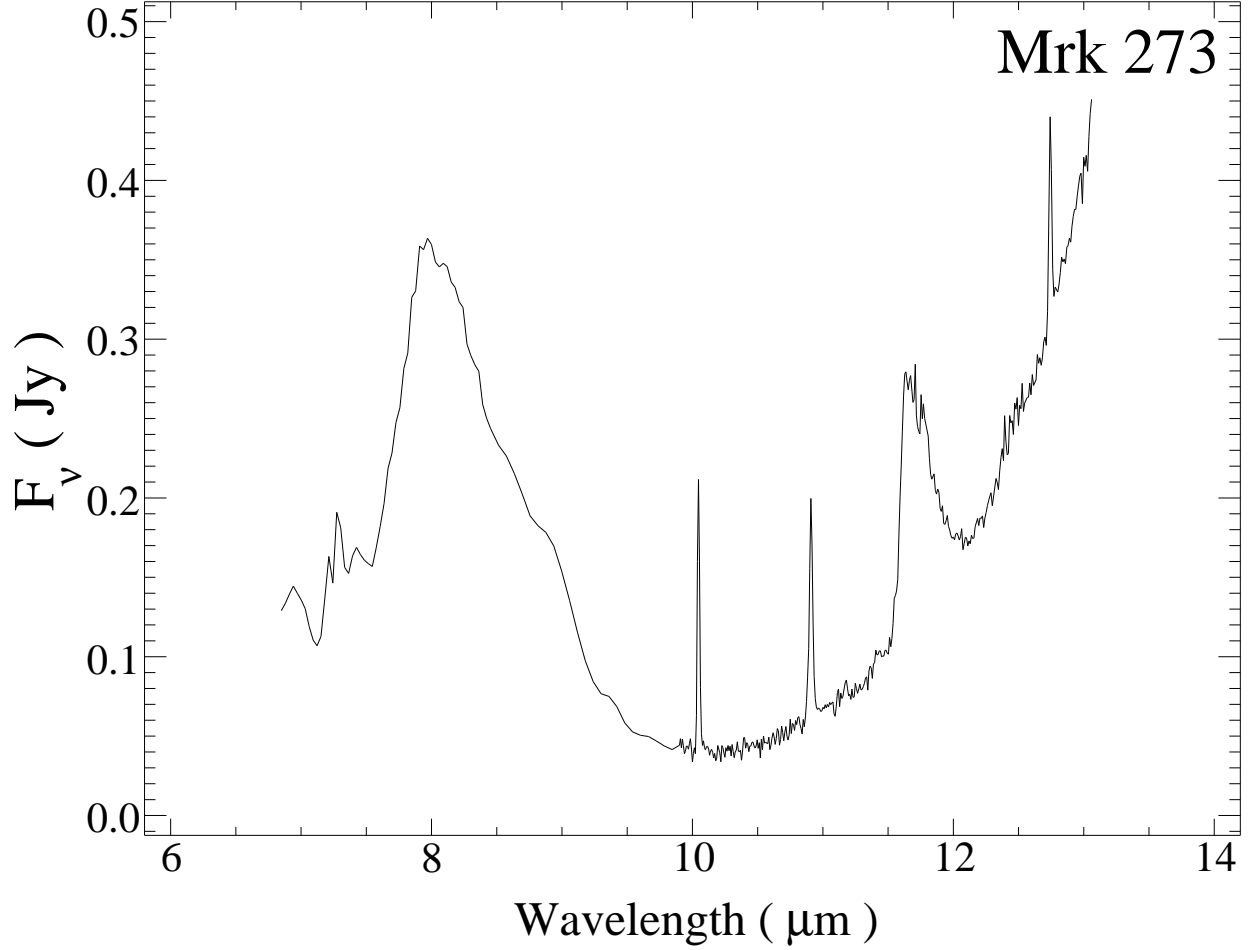


Fig. 5.— The combined IRS-LORES (6.5-9.8 μm) and IRS-HIRES (9.8-13.1 μm) spectrum for Mrk 273. The x-axis is the observed wavelength. A deep 9.7 μm silicate absorption trough is apparent, indicating heavy extinction ($A_V \sim 20\text{-}40$) towards the active nucleus. On the other hand, the ratio of the S(3) 9.67 μm to S(2) 12.28 μm H₂ lines infers much lower levels of extinction, implying that little of the absorbing material lies in a screen between the warm H₂ and us.

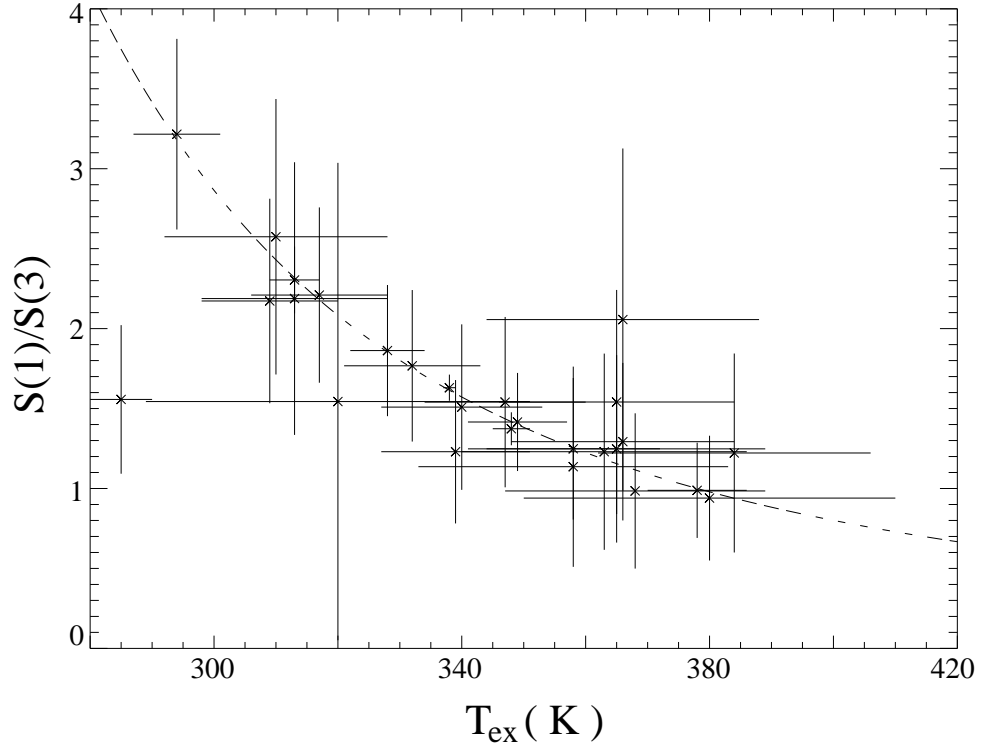


Fig. 6.— Molecular hydrogen $S(1)/S(3)$ line ratios as a function of the derived temperature (T_{ex} for twenty-seven ULIRGs (excluding Arp 220 and IRAS 12112+0305) with at least three $J \leq 4$ HIRES line measurements. The intrinsic (unreddened) ratio is shown as a dashed line. Extinction towards the warm H_2 component is minimal in most of the sources.

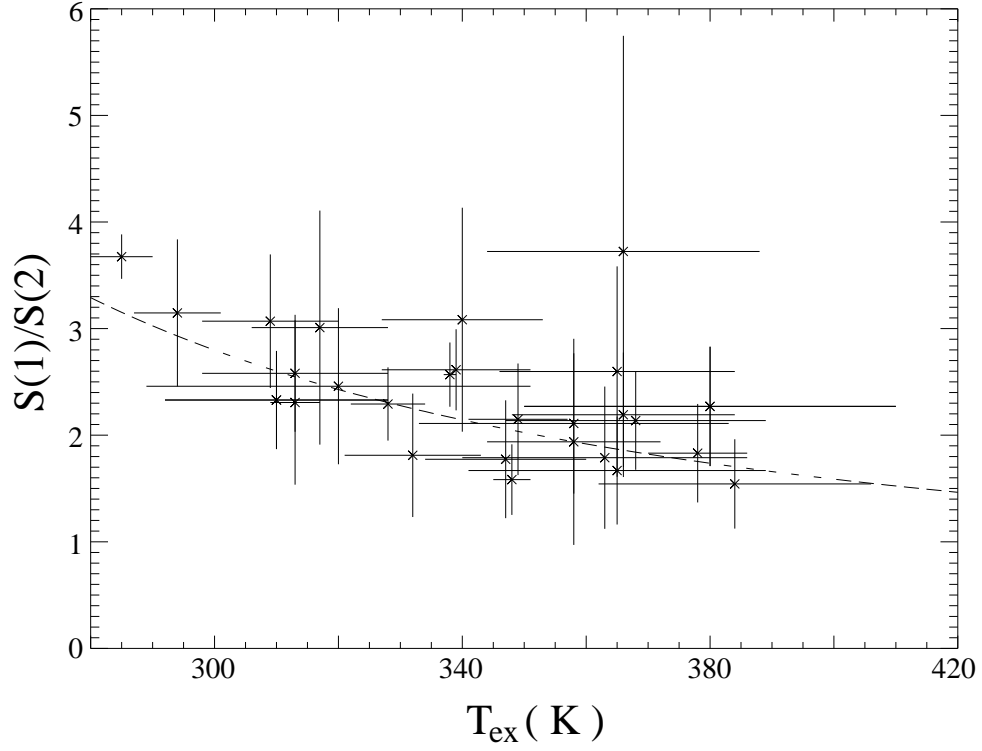


Fig. 7.— Molecular hydrogen $S(1)/S(2)$ line ratios as a function of the derived excitation temperature (T_{ex}) for the twenty-seven ULIRGs in Figure 8. The dashed line shows the expected trend for an ortho-to-para ratio of three and no extinction, which is consistent with the data.

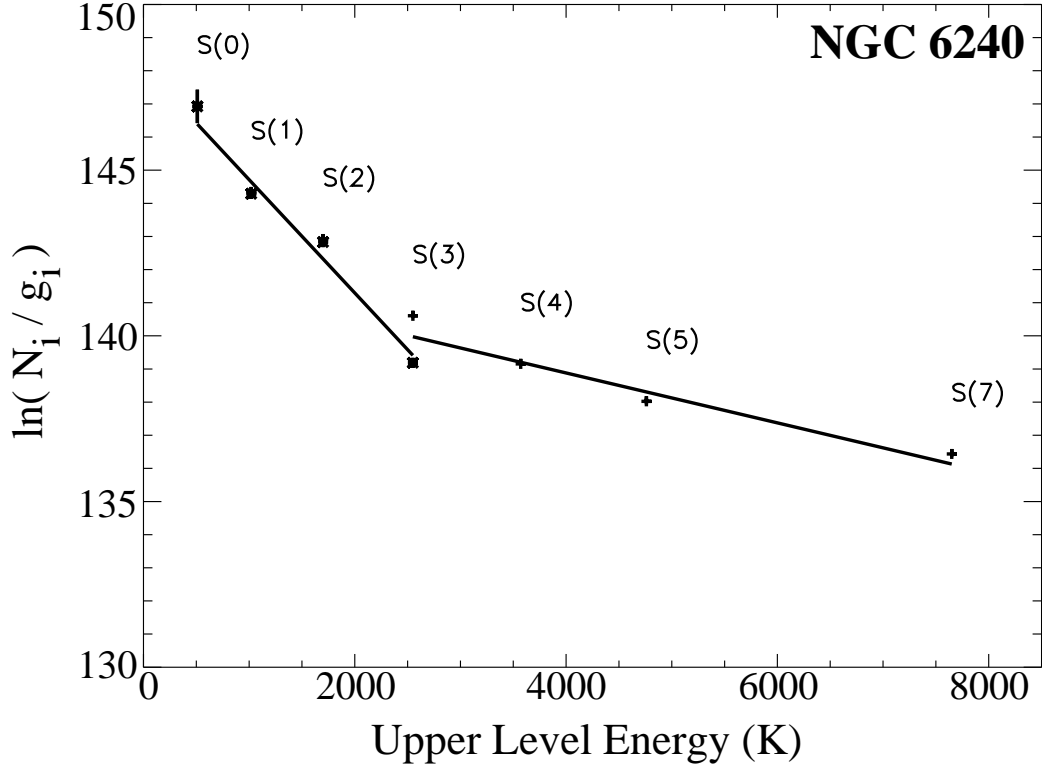


Fig. 8.— Molecular hydrogen excitation diagram for NGC 6240. The S(3) through S(7) values can be fit by with a hot ($T_{\text{ex}} = 1327 \pm 36$ K) H_2 component. A second cooler ($T_{\text{ex}} = 292 \pm 6$ K) gas component is found after subtracting this component from the S(0) to S(3) values (re-plotted as asterisks) prior to modeling.

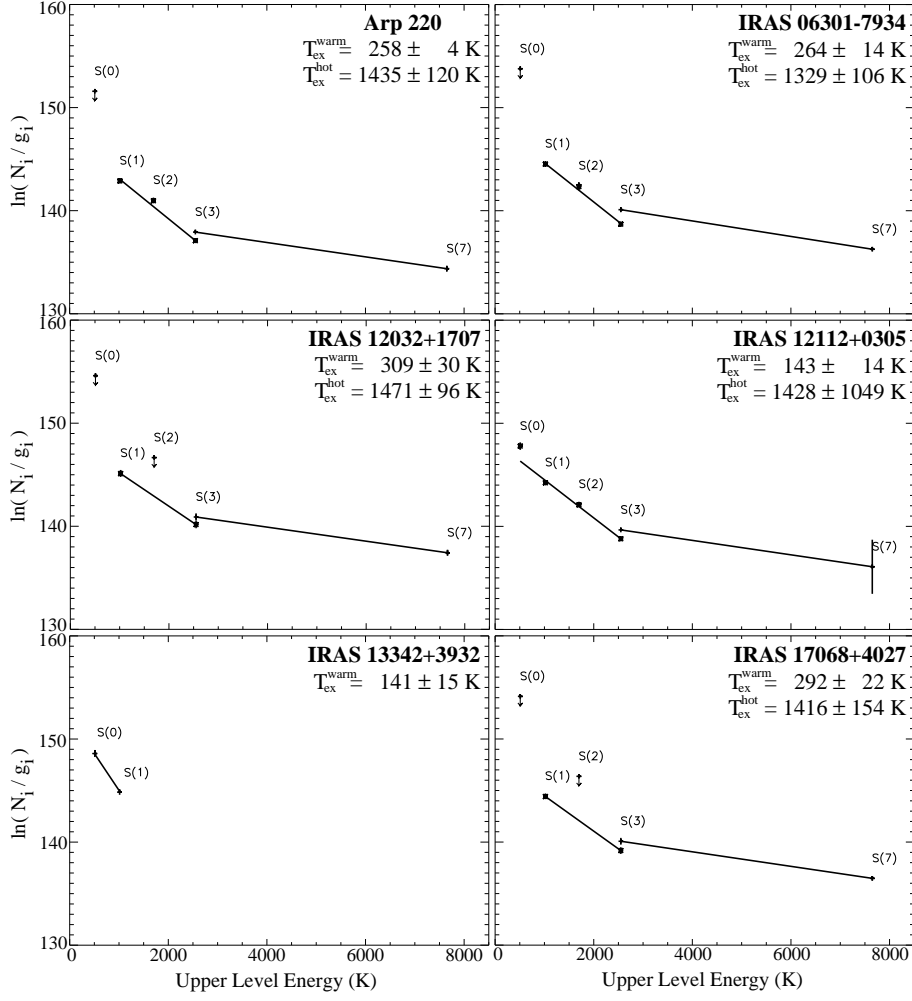


Fig. 9.— Excitation diagrams for the six ULIRGs with either S(0) and/or S(7) line detections. In five sources, the S(7) and S(3) values are fit by a single hot H₂ component, which is subtracted from the S(0) through S(3) values (or limits) to characterize molecular hydrogen gas at a cooler temperature. The derived warm ($T_{\text{ex}}^{\text{warm}}$) and hot ($T_{\text{ex}}^{\text{hot}}$) excitation temperatures are given in the upper-right of each panel.

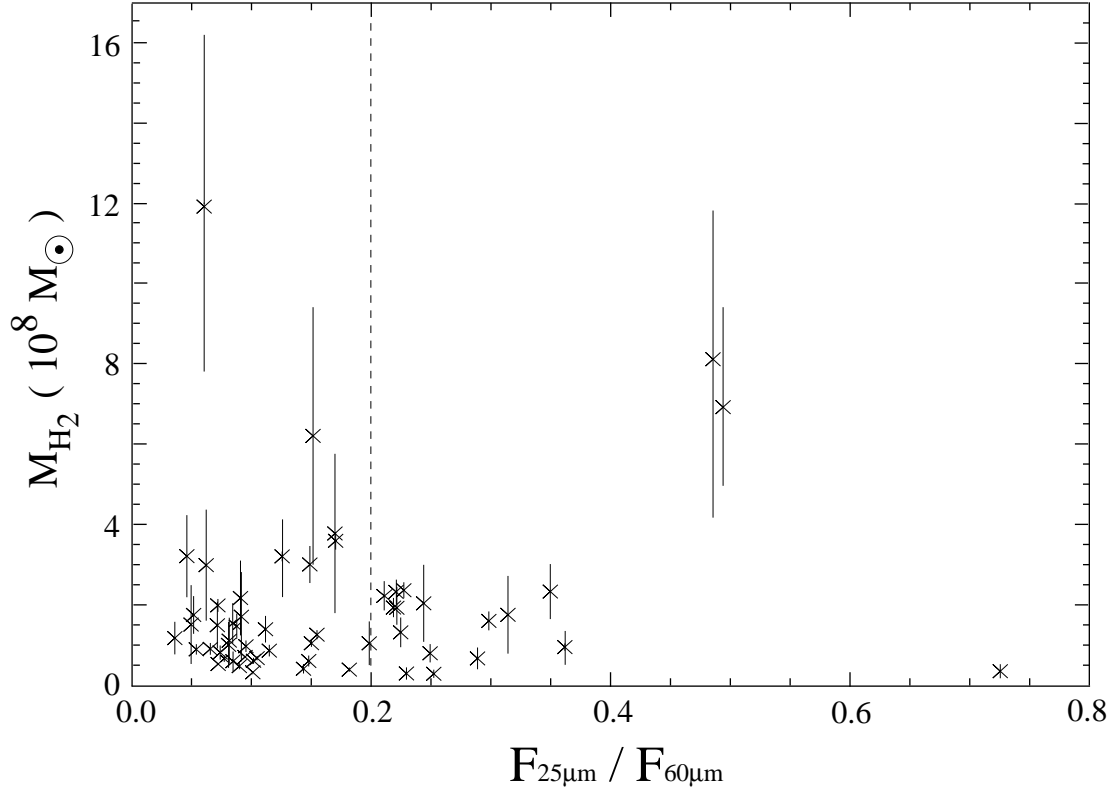


Fig. 10.— The derived warm H₂ masses for the ULIRG sample as a function of their IRAS 25 μm to 60 μm flux density ratios. The vertical line ($F_{25\mu\text{m}}/F_{60\mu\text{m}} = 0.2$) is thought to separate sources dominated by starbursts ($F_{25\mu\text{m}}/F_{60\mu\text{m}} < 0.2$) from those powered primarily by an enshrouded active nucleus ($F_{25\mu\text{m}}/F_{60\mu\text{m}} > 0.2$). No obvious relation between warm H₂ mass and $F_{25\mu\text{m}}/F_{60\mu\text{m}}$ is present.

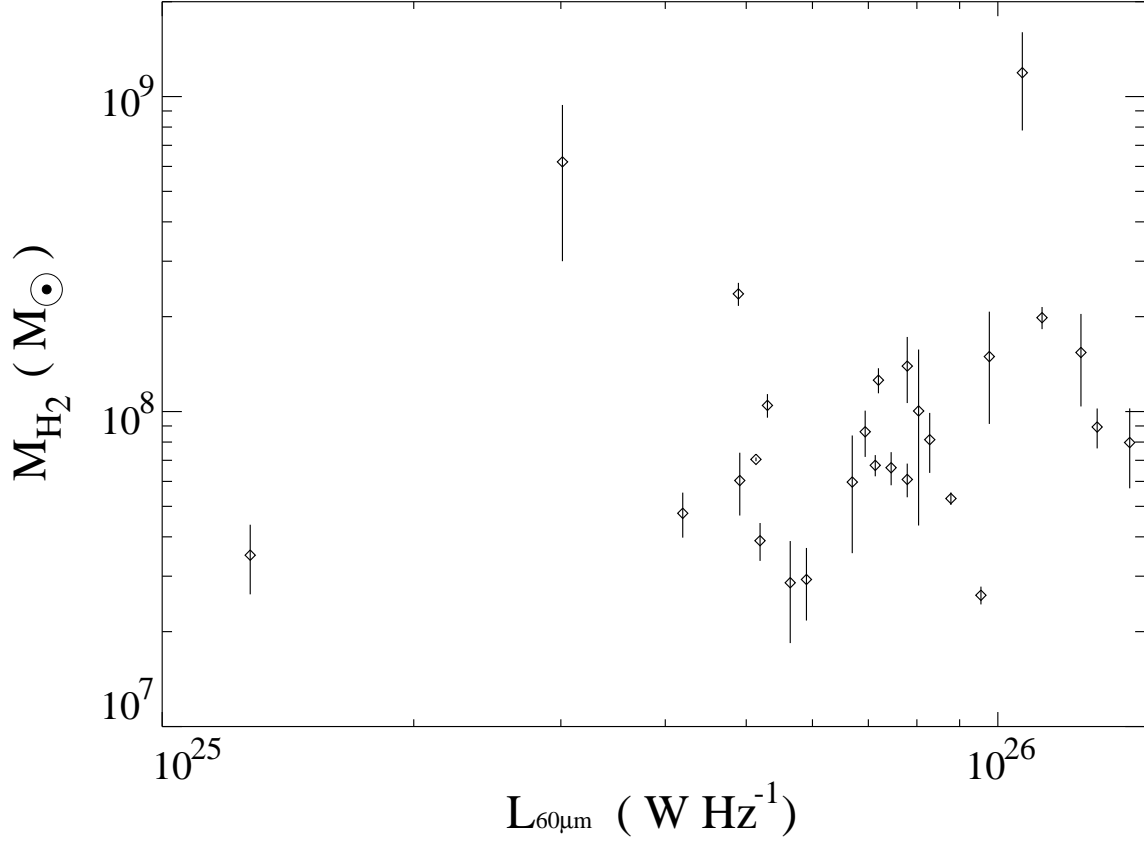


Fig. 11.— Warm H₂ masses as a function of the IRAS derived 60 μm specific luminosity ($L_{60\mu\text{m}}$, in W Hz^{-1}) for the twenty-seven ULIRGs with $z < 0.1$. There is no clear tendency for more 60 μm luminous ULIRGs to possess larger M_{H_2} .

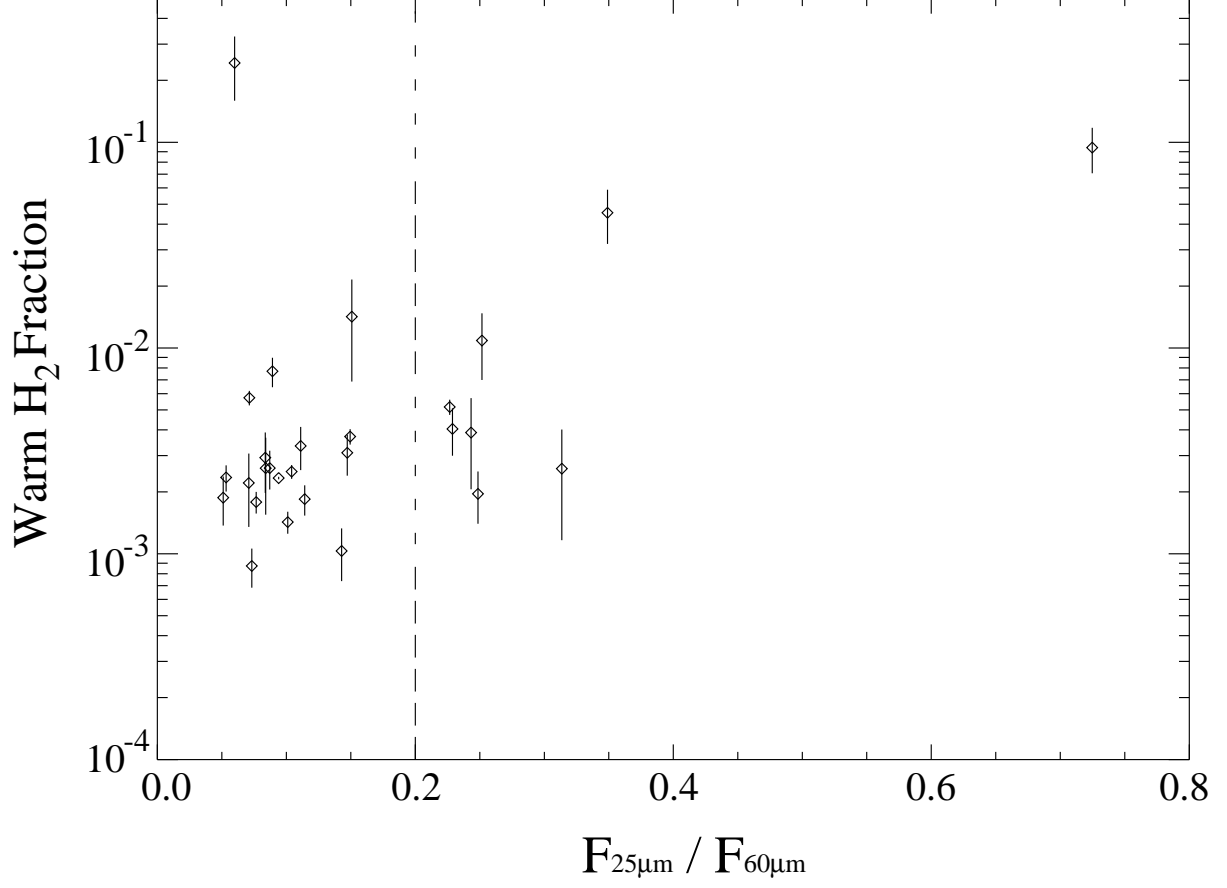


Fig. 12.— The ratio of the warm H₂ mass to the cold H₂ mass from ¹²CO observations as a fraction of the IRAS 25 μm to 60 μm flux density ratio. The dashed line separates “cool” and “warm” ULIRGs, i.e., those that appear to be powered primarily by obscured starbursts or active nuclei, respectively.